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Composite and Multiple Intrusions of Lamlash-Whiting Bay Region, Arran

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ABSTRACT

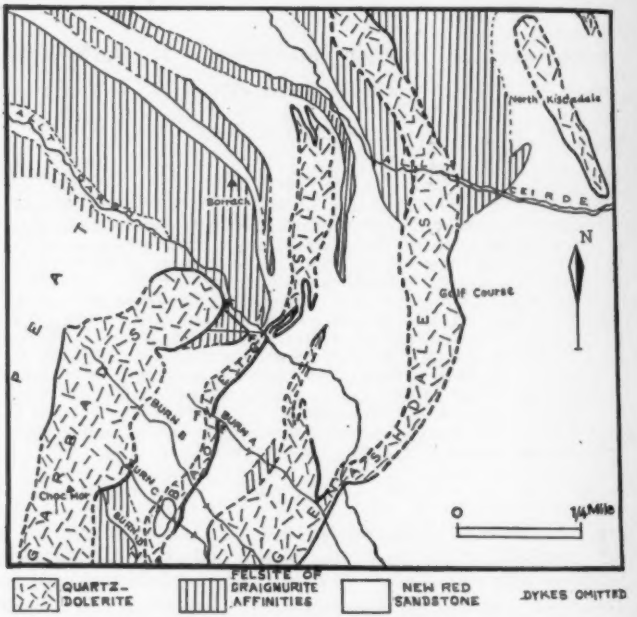
In South-East Arran there are many Kainozoic composite and multiple intrusions, mostly in the form of sills, composed of basic, intermediate, and acid rocks, xenolithic enclosure of basic members by less basic ones being common. The pyroxene of all the rock types is a normal augite and not a pigeonite. Contact hybridization has played an important role in the partial or complete digestion of xenoliths. The genesis of the different members of the intrusions is attributed to the complex process of deep-seated hybridization of two types of magmatic material of contrasting basic and acid composition. The order of injection of magma is, invariably, from basic to acid, though in the intrusions, the spatial sequence of the rock types varies much; their complicated structures are ascribed to a series of pulsations of contaminated magma with its composition tending progressively in the acid direction.

INTRODUCTION

IN South-East Arran, igneous intrusions of Kainozoic age are emplaced in Triassic marls and red sandstones. They represent different episodes of igneous activity and include sills of crinanite, composite and multiple intrusions of basalt and felsite, sills and dykes of acid rock, and a swarm of dykes of basalt and tholeiite. The more important composite and multiple intrusions, most of which are in the form of sills, are to be seen in all the districts of the British Tertiary Province.

A composite sill, according to Daly (1933, p. 79), is " a compound intrusion of sill form and relations and is the result of successive injections of more than one kind of magma along a bedding plane ", while a multiple sill " is the result of successive injections of one kind of magma ", though according to Bailey, Thomas, and others (1924), the latter type of intrusion may be composed of rocks of different composition, but shall have chilled contacts. Harker (1904) from his classic work in Skye found that the different members of an intrusion grade into one another in the field, inferred that the acid injection is

always later than the basic one and postulated the existence of local magma reservoirs. Later work, mostly in Mull by Bailey, Thomas, and others (op. cit.), in Arran by Tyrrell (1928), and in Ardnamurchan by Richey, Thomas, and others (1930), while mainly confirming his conclusions has pointed to some abnormalities in the order of injection as deduced from field relations. Thus, though much has been said on



TEXT-FIG. 1—Geological Map of Whiting Bay Region.

the subject, several of the problems connected with it, such as the mechanics of intrusion, the origin of the magmas, and the role of hybridization remain controversial.

FIELD RELATIONS

(*a*) *Composite Sills.*—One of the largest composite sills in the Lamblash–Whiting Bay region is that exposed in Glen Ashdale. It has a maximum estimated thickness of 210 feet. Emplaced in the soft Triassic sandstones, it extends in an approximately east–west direction for nearly a mile south of Glen Ashdale and to the north of the Glen for nearly a mile and a half; but there veering towards

N.E.–S.W. and N.N.E.–S.S.W. (Text-fig. 1). The best section of the sill is seen in Glen Ashdale–Allt Dhepin. It has been figured and described in detail by Tyrrell (1928, pp. 124–5). The sill is composite in character in having basic and acid rocks as its components in the following order from top to bottom:—

Upper felsite
Quartz-dolerite (feldspathic)
Quartz-dolerite
Lower felsite

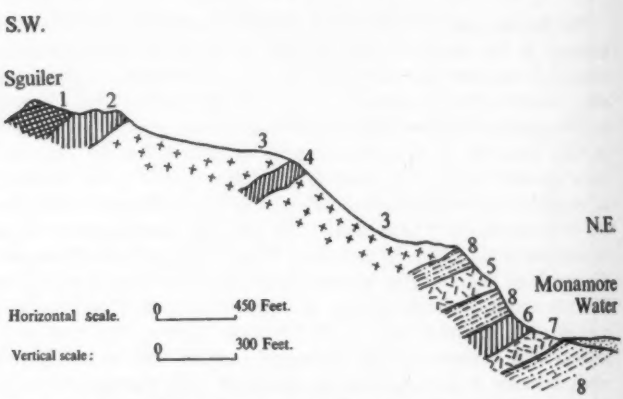
The Baoileig sill, a more or less complete vertical section of which is exposed in the gorge of Allt Dhepin, is 40 feet in thickness and its field relations have been dealt with in the Arran Memoir. Among other sills, mention may be made of the Allt Dhepin–Loch na Leirg sill, an intrusion of great thickness and extent, well exposed in the gorge at Sloc Ruaridh as big columns and composed, for the most part, of a greyish felsite with subordinate " blue-basalt ", or craignurite of roughly intermediate composition, the North Kiscadale sill (Text-fig. 1) made up of " blue-basalt ", as also the Knockenkelly sill and Auchencairn sill. The 30 feet thick Creag Dubh sill on the shore in the south of Whiting Bay is constituted of quartz-dolerite and felsite. The sill south of Gortonallister and east of Lag an Deer extends in a N.W.–S.E. direction west of the Lamlash–Whiting Bay road in that locality and is shown in the geological map of 1947 as of crinanite, when actually it is composite in character with quartz-dolerite and craignurite as its members.

(*b*) *Garbad Multiple Sill.*—This is by far the largest quartz-dolerite sill in South-East Arran with a thickness estimated at 250 feet and extending from south of Cnoc na Garbad in an approximate north–south direction for over a mile up to the gorge in Allt Dhepin where-from it bifurcates, the western branch continuing along Allt Dhepin in the same direction for over half a mile, while the eastern one runs N.N.E. nearly a mile and abruptly ends against felsite near Creag Bhan in Allt Garbh (Text-fig. 1). Allt Dhepin affords a clear section of the intrusion the base of which is seen south of Cnoc na Garbad where the dolerite assumes a vitreous aspect. Further north, the sill rock is coarse-grained and very feldspathic, in places thin veins of a light yellowish-white felsite traversing it. The upper contact of the sill is seen in the western headwater of Burn A, north of Glen Ashdale, the rock there being a compact, ash-grey craignurite. Thus, the sill rock shows considerable variation in appearance and composition, the sill itself with its interior contacts clearly illustrating a multiple character.

(*c*) *Tighvein and Sguiler Intrusions.*—They occupy the high ground

about 6 miles to the interior of the Whiting Bay coast. The Sguiler intrusion is genetically related to the composite intrusions in containing the usual basic and acid components, but as augite-diorites and granophyres respectively. Likewise, the acid intrusion of micro-granite surrounding Tighvein is essentially similar to the several other acid sills of felsite in the region.

A section of the formations from Tighvein south-east towards Allt nan Clach, figured by Tyrrell (1928, p. 134), indicates a diorite mass overlying microgranite which, about 500 yards below in the peat,



TEXT-FIG. 2.—Profile Section from Sguiler to Monamore Water, Arran.
1. Quartz-augite-diorite intrusion. 2. Felsite sill. 3. Monamore crinanite sill. 4. Felsite sill, intruded into crinanite. 5. Quartz-dolerite sill. 6. Felsite sill. 7. " Blue-basalt " sill. 8. Sandstone.

gives place again to a dioritic rock. A section (Text-fig. 2) from Sguiler towards Monamore Burn is of interest in that it reveals the various igneous intrusions in the region with that of Sguiler at the top. Intruded below the Sguiler mass of xenolithic augite-diorite is a felsite sill which overlies the Monamore crinanite into which is intruded a thin sill of felsite. On a horizon lower than the base of the crinanite sill is a quartz-dolerite sill which is but an eastern extension of that exposed in Sguiler Burn. Further down, almost close to Monamore Burn, is a composite mass of felsite and " blue-basalt " resting on New Red Sandstone. This section differs from the one figured by Gregory and Tyrrell (1924, p. 419) in revealing an additional quartz-dolerite sill in the lower reaches near Monamore Burn, and it is seen that the Sguiler mass is made up of xenolithic augite-diorite and not of crinanite.

Petrography

The rocks of the various composite, multiple, and related intrusions can be broadly classified into two groups, the basic and the acid, with several transitional types belonging roughly to an intermediate group, all of which are quartz-bearing. They exhibit considerable variation in texture and grain size from compact, almost glassy varieties through fine-grained to medium-grained ones.

(i) *Basic and Sub-basic Rocks.*

Quartz-basalt.—This is by far the most basic rock and is generally encountered as thin, xenolithic bands sharply demarcated from the enclosing sub-basic, intermediate, or sub-acid rock. It is dark and fine-grained. In thin section, it contains augite as irregular crystals and short rounded prisms pseudomorphed by brownish hornblende or pale green scrappy chlorite, a little plagioclase, some hornblende and biotite, abundant skeletal and rod-like iron-ore and where present mesostasis of dusty alkali-feldspar. But where it occurs as a xenolith in a less basic rock such as quartz-dolerite, it is thoroughly veined and permeated with feldspathic material which decreases in amount towards the central part of the xenolith. At the contact the enclosing rock is relatively fine-grained, having some biotite and a high proportion of iron-ore. These features indicate the migration of the acid constituents from the enclosing magma and their fixation in the xenolith and of basic constituents from the latter to the former.

Vesicular patches are very common in the quartz-basalt particularly close to the contact with the enclosing rock and are made up of calcite with occasional grains of quartz. Such an association of druses with xenoliths has been recorded by Harker (1904, p. 135). The growth of euhedral crystals of green-brown hornblende and, less commonly, of flaky fawn-brown biotite on the edges of the vesicles outwards into the acid mesostasis is significant. Such ferromagnesian minerals evidently result from the interaction between the xenolith and the late-formed acid residuum of the enclosing magma.

Quartz-dolerite and its Variants.—The commonest basic member of most of the sills is a quartz-dolerite almost identical with the Talaidh type of quartz-dolerite in Mull. It is a dark grey, mostly fine-grained, non-porphyritic rock exhibiting, in thin section, the characteristic ophitic texture with well-shaped plagioclase laths, pyroxene prisms, and iron-ore euhedra in an abundant, dusty-brown mesostasis containing blebs of quartz and needles of apatite.

The plagioclase ($2V_\gamma$ mostly 74° to 75·5°; An_{55}) occurring as unaltered stumpy laths is faintly zoned and generally exhibits undulose extinction. The commonest pyroxene is a colourless or occasionally pale green augite as prismatic crystals with a salite striation on (001).

It is mostly unaltered but here and there shows marginal development of yellowish-green hornblende. It encloses and also has moulded on it crystals of iron-ore. Determinations of optic axial angle on several grains in different micro-sections ($2V_\gamma$ mostly between 46·0° and 47·5° and occasionally reaching 50·0°; $\gamma \wedge c$ 47·5°) confirm it as augite, a fact which is in accordance with the observation of Hess (1941). Besides augite, there is rhombic pyroxene which occurs as long prismatic crystals with well-developed cleavage and mostly altered to bastite, some iron-ore having been liberated during the alteration. Part of it is enstatite ($2V_\gamma$ 68°), while the rest is hypersthene ($2V_a$ 75°; X = yellow, Y = pale pink, Z = pale green). Iron-ore is abundant and occurs as euhedra sometimes rather modified and presenting a skeletal appearance. The turbid mesostasis is mostly made up of dusty alkali-feldspar which seems to be in intergrowth with quartz, the quartz occurring as minute blebs and threads in the micropegmatite besides as irregular areas. Considerable variation in the coarseness and relative proportions of the two constituents in the intergrowth is noticeable. Veins of microcrystalline felsitic material occasionally traverse the rock. Apatite, the most frequent and important accessory mineral, occurs as acicular crystals, singly or in clusters.

Olivine-bearing quartz-dolerite forms the component of one of the successive injections in the Garbad multiple sill in the scarp east of Cnoc Mor. It is very similar to the quartz-dolerite except that it contains, in addition, occasional microphenocrysts of an iron-rich olivine, generally thoroughly altered to dark greenish-brown bowlingite. The rhombic pyroxene exhibits schiller structure and alteration to a rather dark green serpentine. Mesostasis is poorly developed, quartz being less in amount and micropegmatite distinctly rare. Augite, iron-ore, and apatite occur as usual.

Chilled pitchstone-like variants of quartz-dolerite occur in the eastern part of Garbad mass a quarter of a mile south of Torr na Baoileig and are made up of the usual minerals but set in a characteristic brownish-grey glassy base with some acicular crystals of pyroxene and rod and string-like iron-ore. Further, the base contains small amounts of chlorophaeite. The rocks, while being distinctive in themselves, bear a close resemblance to the stony type of basic Leidleite (Mull Memoir, p. 282).

Spherulitic quartz-dolerite and granophyric quartz-dolerite respectively from Creag Dubh sill and Glenashdale sill, show evidence of contamination. With their distinctive textures, they are characterized by a relatively higher proportion of acid mesostasis. Ophitic texture is obliterated to a considerable extent and, in some cases, the feldspar of the micropegmatite is in optical continuity with that of the sodic marginal zones of contiguous laths indicating crystallization during the

same magmatic stage. Pyrogenetic hornblende is common and apatite is very frequent.

Spherulitic texture, as a rule, is rare in sub-basic rocks and in the present instance betrays affinities to the more acid members like felsite.

A plutonic equivalent of the acid varieties of quartz-dolerite is the *quartz-augite-diorite* of the Sguiler intrusion. This rock has a characteristic black-and-white mottling. The microsection contains prisms of colourless augite ($2V_\gamma$ 50·0°; $\gamma \wedge c$ 43°), fibres of euhedral green-brown hornblende ($\gamma \wedge c$ 16° to 20°) moderately pleochroic and with strong dispersion, titaniferous iron-ore, partly as euhedra and partly as spongy masses, ilmenite-biotite intergrowths, and laths of andesine (An_{37}), all in a very abundant granophyric mesostasis. There are relatively clear and dusty areas in the matrix, the former of rather coarse intergrowth between clear albite and quartz and the latter of cryptopegmatite constituted of dusty alkali-feldspar and quartz. The diorite occasionally develops a typical spherulitic texture. Xenoliths of quartz-basalt and quartz-dolerite are also very common. The marginal parts of the xenoliths are resorbed, the xenoliths themselves having suffered considerable acidification as evidence by the crystallization of hornblende and biotite, though in small amounts, out of the pyroxenic material, the albitization of plagioclase as well as its replacement along the peripheries of the laths by micropegmatite and the enrichment in quartz. Most significant of all is the presence in a high proportion of apatite as large crystals, a fact referred to by Nockolds (1933, 1934) in connection with his studies on contaminated rocks and one which indicates preferential absorption of volatiles by the xenoliths. Only when, in rare cases, a basalt xenolith does not have any apatite, the enclosing diorite contains the mineral in abundance instead.

(ii) *Intermediate Rocks.*

A few rock types of a composition in between that of the basic and the acid members, though not necessarily conforming to that of the strictly intermediate division of rocks are included in this group.

" *Thorough* " *Hybrid.*—In the Glenashdale sill most of the rocks that lie close to and on either side of the central bands of quartz-dolerite are seen grading into less basic rocks towards the flanks of the sill and are conspicuous in having a few dark spots or clots in a very feldspathic medium sometimes, in addition, containing dark xenoliths. They are rather fine-grained and blackish-grey in colour with an average specific gravity of 2·71 as contrasted with 2·80 for the adjoining quartz-dolerite. In thin section, they are composed of two contrasting types of elements, a pyroxene-plagioclase and iron-ore-bearing material,

and a micropegmatite-bearing portion. In all, hornblende, a little biotite, some pyroxene, plagioclase, and iron-ore are present in a very abundant granophyric mesostasis. Hornblende is very conspicuous as euhedral, rather rounded or irregular crystals with a red-brown tint and strong dispersion. Characterized by lack of form and cleavage, the flakes of biotite exhibit pleochroism from yellow-brown to blood-red. In addition to augite, hypersthene and iron-ore, some dusty brown limonite occurs. Plagioclase ($2V_\alpha$ 82°; An_{38}) with its rather low relief seems to grade into the clear feldspar of the mesostasis. It occurs as squarish laths commonly untwinned but zoned. The mesostasis which is abundant is markedly pellucid in character and is granophyric, being made up mostly of micropegmatite. Quartz, besides that in the intergrowth, is commonly interstitial. Apatite is very common and, significantly, zircon is also present as an accessory. Partially digested xenoliths of fine-grained basalt sometimes occur.

This rock which illustrates the intimate association of two contrasting mineral assemblages is referred to here as a " thorough hybrid " in the absence of a perfect similarity with any of the common igneous rocks.

Craignurite.—As observed by Tyrrell (1928, p. 141), rocks showing the characteristic texture and mode of crystallization of craignurites are generally rare in Arran. Still, by virtue of their composition and mode of occurrence as members of composite and related intrusions, some rocks of this region fall under the category of craignurite, which, as described here, corresponds with that of the intermediate type of Mull.

The rock is fine-grained and light grey coloured with hardly any recognizable constituents. Under the microscope it consists of a few microporphyritic crystals of plagioclase (basic oligoclase to acid andesine) in a network of long narrow prisms of augite altered to chlorite, typically skeletal crystals of iron-ore set in a crypto- or micro-crystalline base containing albite or soda-orthoclase. Interstitial quartz is very common. Micrographic intergrowths, such as those common in the rock from Mull, are not found. Apatite as an accessory is usually high in amount. Zircon is occasionally present. In several cases large vesicles of calcite are encountered. Veining by felsitic material and incipient hybridization are common. The absence of any fresh ferromagnesian mineral, the abundance of chlorite and magnetite along with the very high proportions of alkali-feldspar and interstitial quartz, the general richness in calcite and the presence of apatite in more than accessory amounts are all the unique features of the rock. It is this rock that constitutes the major part of the two thin sills, one in North Kiscadale and the other south of Gortonallister. It occurs as definite bands in most other masses.

Several quartz-dolerites and quartz-basalts on extensive acidification give rise to rather intermediate types which, while still partly retaining their original characters, very rarely develop anything like a skeletal habit. All these variants in the intermediate group are referred to as hybrid rocks with affinities to craignurite, which appears to represent but one of the many products of crystallization from a contaminated magma of approximate intermediate composition.

(iii) *Acid Rocks.*

Felsite and granophyre of craignurite Affinities.—These rocks of

TABLE 1

	1	2	3	4	5	6	7
Plagioclase . .	18·3	28·7	32·0	18·3	12·8	8·0	9·7
Na-orthoclase (micro-porphyritic) . .	—	—	—	—	—	10·5	
Quartz . . .	20·4	4·6	6·5	6·4	4·7	10·1	29·2
Mesostasis . . .		30·1	33·9	52·0*	57·8*	60·6	55·3
Pyroxene + chlorite .	15·6	23·4	8·9	8·8	14·3	3·2	1·2†
Hornblende + biotite .	—	—	—	7·4	—	—	—
Iron ore . . .	30·2	10·6	8·1	7·1	10·4	3·5	4·6
Apatite . . .	—	1·9	2·0	—	—	—	—
Calcite . . .	15·5	0·7	8·6	—	—	4·1	—

* Includes apatite and calcite.
† Chlorite.

1. Quartz-basalt ; average of three specimens.
2. Quartz-dolerite ; average of six specimens.
3. Quartz-augite-diorite ; average of four specimens.
4. " Thorough "-hybrid ; average of three specimens.
5. Craignurite ; average of six specimens.
6. Felsite of craignurite affinities ; average of six specimens.
7. Microgranite ; average of three specimens.

yellowish-white colour and fine grain, the commonest in the region, represent the acid members of the intrusions. Most often, they have relics of slightly darker xenoliths of coarser crystallization. The xenoliths are either of quartz-dolerite or less coarse-grained quartz-basalt and are much acidified, containing idiomorphic hornblende, albitized plagioclase, and a fairly high proportion of quartz and alkali-feldspar with or without micropegmatite. The enclosing acid rocks show a few microphenocrysts of rounded and corroded quartz, and of soda-orthoclase, albite, and albite-oligoclase (An_{15-19}; $2V_a$ mostly 87° to 88°, rarely 90°), in a minutely crystalline, very abundant, turbid, feldspathic or granophyric base. The ferromagnesian element is represented by a little chlorite and disseminated scrappy iron-ore.

Interstitial and drusy quartz abounds. Apatite is an important accessory. The affinities of the acid rocks with craignurite are, therefore, demonstrable in respect of their texture and mineralogy.

Microgranite.—This rock which forms the acid intrusion surrounding Tighvein is light greyish-yellow, minutely granular, and has sporadic rectangular crystals of feldspar. Under the microscope, the typical microgranitic texture can be seen, the bulk of the crystals of quartz and feldspar being anhedral. The microporphyritic feldspar, albite-oligoclase, and soda-orthoclase has a kind of fingerprint structure like the one figured by Smellie (1913). Anhedral quartz is abundant and

TABLE 2

	1.	*2.*	*3.*
SiO_2 .	49·66	54·00	52·49
TiO_2 .	1·93	2·83	1·21
Al_2O_3 .	13·48	13·09	13·36
Fe_2O_3 .	2·68	3·53	1·23
FeO .	9·81	8·45	11·35
MnO .	0·22	0·37	0·32
MgO .	3·82	3·49	1·96
CaO .	7·64	5·55	6·24
Na_2O .	2·32	3·27	3·18
K_2O .	1·20	1·80	1·42
H_2O+ .	0·56	1·71	1·24
H_2O- .	0·73	1·26	0·30
CO_2 .	5·94	0·25	5·06
P_2O_5 .	0·23	0·31	0·84
	100·22	100·07*	100·20

* Includes FeS_2 0·14, BaO 0·02.

1. Quartz-basalt (W74), Auchencairn Sill, Whiting Bay, Arran (analyst, W. H. Herdsman).
2. Quartz-dolerite, Garbad Sill, Whiting Bay, Arran (Tyrrell, 1928, p. 147).
3. Quartz-augite-diorite (W162), Sguiler intrusion, S.E. corner of Urie Loch, Lamlash, Arran (analyst, W. H. Herdsman).

dovetails the feldspar suggesting a micrographic intergrowth. Pale yellow pseudomorphous chlorite and a few specks of iron-ore are the sole mafic constituents. Zircon is a prominent accessory.

MINERALOGICAL AND CHEMICAL COMPOSITION

The average modal composition (volume per cent) of the principal rock types described in the former pages is presented in Table 1, and chemical analyses of three of the rocks are given in Table 2.

PETROGENESIS

Though the absence of any strictly intermediate member in the intrusions described above may be ascribed, on the basis of Bowen's

(1928) hypothesis, to high fractionation, it is apparent that any straightforward differentiation relation between the different members of the igneous masses does not exist. In addition, there are the basic xenoliths that definitely demonstrate some stages in the process of hybridization. The process may be considered as belonging to two phases, contact and deep-seated. The latter type, which is more prevalent, is to be seen in all the rocks, the former in their xenoliths and aureoles of contamination.

The course of contact hybridization has been one of transfer of calcic material from the xenoliths to the acid members and the migration of alkali material to the basic members, a process demonstrated under the name of reciprocal reaction by Read (1924) and by Thomas (1922). Fine-grained basalt xenoliths are very common in the felsites and granophyres and, in general, they seem to suffer mechanical disintegration, and get enriched in alkali feldspar, hornblende, and biotite as also in calcite, apatite, etc., all the transformations being attributable to interaction between the enclosed bodies and the enveloping acid magma. Further, the xenoliths exhibit in themselves the different stages of digestion, a number of gradations from the dark slightly modified basaltic bodies of somewhat angular outlines to the more or less thoroughly transformed rounded masses of grey-coloured craignurite being encountered. But, if as is universal here, the whole of the basic solid material was not made over to a composition stable under the conditions of crystallization of acid magma, it was because of the meagre superheat in the acid magma consolidating in the upper levels of the earth's crust and of the limited assimilation that hastens the cooling processes, facts long ago established by Bowen (1922). In addition, significantly enough, in no case did an acid magma chill against a solid basaltic xenolith. It very clearly indicates that though the xenolith was solid when picked up by the acid magma, it was at a temperature higher than that of the crystallization of the latter. Thus, there is evidence that the basic magma, which is the source of the xenoliths and which has a far higher temperature of crystallization than that of the acid, had crystallized but, in all probability, for want of time, had never cooled down to a temperature lower than that of the acid before the acid magma invaded it. The basic magma has been much contaminated by the acid one to give rise to quartz-augite-diorite at depth and the acid magma, in turn, has been basified, though here not to the same extent as the basic magma was acidified. Its products of consolidation, felsites of craignurite affinities, granophyres, and contaminated microgranites, wherever they occur, bear testimony for this mode of origin in the rather high proportion of dark minerals they contain. That the hybridization was undoubtedly of the deep-seated type and also that it was prior to the intrusion of

the respective magmas is proved by the fact that all the consolidated products, though anomalous from the petrographic viewpoint are quite nearly homogeneous and in most cases even closely resemble the corresponding " normal " rock types.

The " thorough hybrid " with the sub-ophitic and granophyric textures in close association, and with pyrogenetic hornblende, is undoubtedly the result of crystallization of a deep-seated contaminated magma.

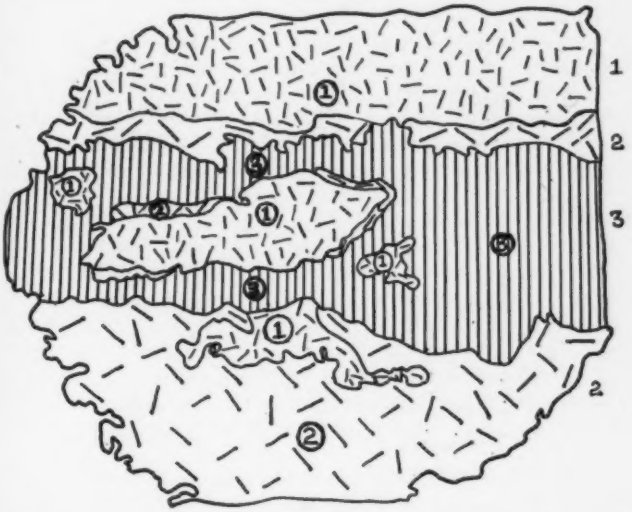
Mixing in simple proportions of two contrasting magmas respectively of basic and acid composition implies that the resultant hybrid magma and its products of consolidation must be theoretical mixtures of the end members in simple proportions and further that there is no scope for partially digested solid bodies (xenoliths) to occur in them. In other words, there should be a straight line variation between the different resultant hybrids and they should all be strictly homogeneous in themselves. Most of the rocks described above are, on the contrary, of a rather heterogeneous texture and are generally xenolith-bearing and these features conclusively prove the inclusion, followed by some digestion, of solid bodies in a magma. Thus, though the importance of the process of hybridization in rock formation is established, the amount of mixing and the incorporation of one type of material by the other seems to be generally limited. The strictly intermediate types of rock with basic and acid elements in equal proportions are rare, most of the hybrids being the products of contamination within a narrow range of either of the magmas. It is confirmed, further, by the occurrence of the hybrids more in relatively smaller patches as local types of rock than as regional masses.

Whatever the course of hybridization be, it is certain that the existence of a basic and an acid magma and their intermingling in depth could give rise to a wide variety of rocks. But, the ultimate source of the two magmas is still a matter of controversy. Harker (1904) maintains that they are complementary differentiates from a single parent magma, while Bailey, Thomas, and others (1924, p. 33) confirming the view further suggest that the basic differentiate was regenerated as a magma by the melting of sunken crystals. But, in view of Grout's (1926, p. 549) important calculation that as a maximum one-tenth of an average basaltic magma may become granite, it becomes difficult to explain so large a volume of acid magma as to dominate the basic material in the Arran intrusions. Even granting that such a differentiation did result in a huge volume of acid rock, it is most improbable that there should not be any primary rocks whatever of a composition truly intermediate between the acid and the basic. Hence one is forced to the conclusion that the two different magmas could not have been derived from a parent basalt magma

by any sort of differentiation whatsoever. The volume of acid magma required could have been produced by melting of the crustal material as advocated by Holmes (1931) or by rheomorphism as conceived by Krokstrom (1937).

Mechanics of Intrusion

While as pointed out by Tyrrell (1928, p. 141) many of the sill-



Text-fig.—3. A microsection showing association of different rock types. (×4)

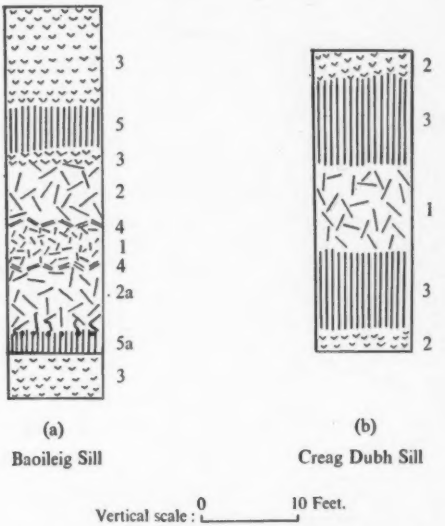
1. Quartz-basalt. 2. Quartz-dolerite. 3. Felsite of craignurite affinities.

rocks dealt with here resemble closely those of the Cnoc Carnach group of composite sills in Skye, the same cannot be said to hold good as far as the constitution and relative arrangements of the components in the sills are concerned. The constitution in the majority of cases is not triple in the sense that a basic member lies on either flank of the acid centre but much more complex.

The order of intrusion always seems to obey the general rule, viz. from basic to acid. A microsection (Text-fig. 3) showing association of different widely contrasting rock types clearly illustrates the point. It is seen that quartz-dolerite invaded the quartz-basalt along the margin

and also has picked up the same as xenoliths. Both of them were invaded by felsite of craignurite affinities which cuts the quartz-dolerite and has picked up xenoliths of quartz-basalt which are rimmed by the later-formed quartz-dolerite. These rims, however, are lost for some xenoliths signifying, again, the incorporation of the doleritic rock by the acid felsitic material.

The arrangement of the rock types in the 40 feet thick Baoileig



TEXT-FIG. 4 (*a*).—1. Fine-grained quartz-dolerite. 2, 2a. Acidified quartz-dolerite. 3. Craignurite. 4. " Thorough " hybrid. 5, 5a. Felsite.
TEXT-FIG. 4 (*b*).—1. Acidified quartz-dolerite. 2. Craignurite. 3. Felsite.

sill can be represented diagrammatically as in Text-fig. 4*a*. The sill, broadly speaking, is quintuple having a central mass of acidified quartz-dolerite with, on either side, a band of felsite which, again is flanked by craignurite. The sequence of intrusion is clear and can be explained as follows :—

First, the fine-grained quartz-dolerite which suffered pre-intrusive acidification is injected. This was followed almost immediately by a further acidified quartz-dolerite. Almost in the same phase was injected the craignurite which both at the top and at the bottom of the sill was chilled exteriorly against the sandstone. More or less simultaneously, the " thorough " hybrid must have been intruded

eviscerating the central mass of acidified quartz-dolerite. At this stage there seems to have been a slight pause before the final injection of the contaminated acid magma along the planes of weakness between the main central mass of acidified quartz-dolerite and the flanking craignurite. This is evidenced by the facts that the basal felsite at its bottom contact becomes fine-grained and very nearly glassy and also that it has picked up xenoliths along its upper contact with the central mass and has been successful in partially digesting them and at the same time sending veins into the quasi-liquid acidified quartz-dolerite as seen in some specimens taken from that horizon. Towards the top the same component has, probably by contact hybridization with the central sub-basic mass, given rise to a very thin band of rock with the characters and composition of craignurite. Thus, it becomes clear that, though the sill is not of any great thickness, it is, nevertheless, characterized by several injections of magma of varying composition, the variation always tending from basic to acid.

Similarly, contaminated magma must have been injected in quick succession in several pulses, each tending to be acid in composition, and the various compositionally different pulsations must have comingled to the utmost again to result in the typically quintuple Creag Dubh composite sill (Text-fig. 4*b*). The structure of the Glenashdale sill could not easily be deciphered because of its unusual thickness and the lack of exposures of good vertical sections in the field. But there is not doubt that though it seems to consist essentially of four components, it actually represents several injections of magma of varying composition.

The Garbad multiple sill exhibits a sufficiently wide variation in its components from as basic a type as olivine-bearing quartz-dolerite through quartz-dolerite, acidified quartz-dolerite and glassy facies of the same of basic leidleite character, to an intermediate rock (craignurite), and this lends support to the view of the authors of the Mull memoir mentioned earlier that a multiple sill is similar to a composite one in containing widely varied rock types.

Acknowledgments

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Composition of Pelites from Connemara, Co. Galway, Ireland

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Abstract

Seventeen Connemara pelites have been chemically and modally analysed and a garnet, a staurolite, and a biotite from them chemically analysed. The results show that these pelites are rather poor in silica and rich in alumina and total iron. It is believed that this was an original feature of the composition.

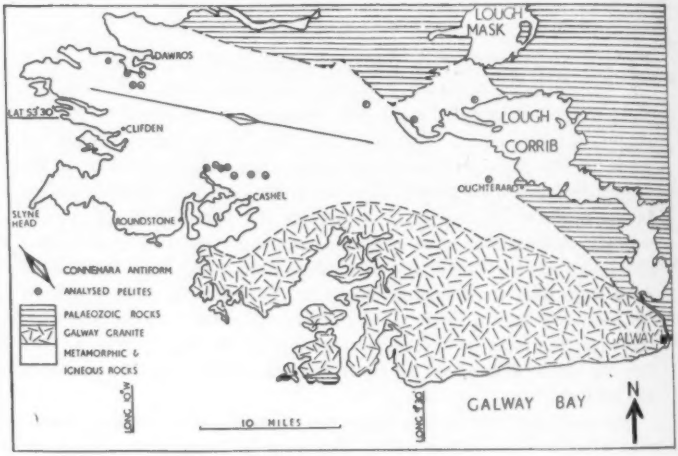
Introduction

THE quartzite core of the Connemara antiform (Text-fig. 1) is flanked to the north and south by more pelitic rocks. The southern flank has been intruded by much synorogenic basic and ultrabasic magma (Leake, 1958). The heat imparted by the magma raised the grade of the regional metamorphism in the neighbourhood of the intrusions from high amphibolite facies to pyroxene hornfels facies. In the aureoles of the larger intrusions the pelites have been very strongly metasomatized (unpublished work by Skirrow and Leake) and have, in particular, been variably dealkalized and desilicated. Away from the intrusions the pelites show little thermal metamorphism but they also have a fairly silica poor composition. Compared with many pelites described in the literature (e.g. D. M. Shaw, 1956, p. 928) they are low in silica (*c.* 44 per cent) and rich in alumina (*c.* 25 per cent) and total iron (*c.* 12 per cent).

The work reported in this paper was carried out in order to determine whether or not these pelites, like those in the aureoles, owe their unusual composition to metasomatism. Eight typical pelites were collected in south Connemara, all from outside the aureoles of the basic or ultrabasic intrusions. These were chemically analysed and compared with nine typical pelites from other parts of Connemara; in particular they were compared with five pelite analyses from north Connemara, because it is known that the regional metamorphism on the northern flank of the Connemara antiform is mostly of staurolite-kyanite facies, not sillimanite-almandine facies as in the south. It was therefore considered that if the unusual features in the compositions of the pelites are an original sedimentary feature then there would be little significant difference between the pelitic compositions, especially the alkalis and silica, in the different areas. If, on the other hand, the unusual features are the result of metasomatism during metamorphism then, because the metamorphism was different in the different areas, the results of the metasomatism would also be different, producing pelites of differing compositions.

With the exception of a few analyses of ophicalcites by Cronshaw (1923) there are no published analyses of any Connemara metasediments. Because of the nature of the problem and the small number of analyses available this account is only concerned with the composition of the pelites and it does not attempt to establish the average composition of the series; pelite—semipelite—siliceous granulite—quartzite. The proportion of pelite in Connemara is relatively small compared with the proportion of semipelite, siliceous granulite, and quartzite.

Methods.—All the modal analyses of the rocks were obtained by



TEXT-FIG. 1.—Sketch map of Connemara.

point-counting (Chayes, 1949) and are expressed as volume percentages. For most of the modal analyses 4,000 to 7,000 points in total were counted on at least two slides but for BE 708 (2,627 pts.) and BE 811 (3,500 pts.) the number was smaller. Niggli (1954, pp. 128–133) has shown that volume percentage-modes and molecular norms are directly comparable and so it is unnecessary to convert volume percentage modes into weight percentage modes.

For the chemical analyses colorimetric, titrimetric, and flame photometric techniques were employed. All the powders were dried at 110° C. for several hours before analysing. SiO_2 was determined by measuring the molybdenum blue colour developed by reducing silicomolybdic acid with metol-sulphite (J. B. Mullin and J. P. Riley, 1955, p. 162). Al_2O_3 was determined colorimetrically by extraction of its

oxinate in chloroform, iron being masked as the ferrous dipyridyl complex. Total iron was determined colorimetrically by reducing it to the ferrous state and complexing it as ferrous dipyridyl. The method of Shapiro and Brannock (1952) was used for TiO_2 and MnO. Na_2O and K_2O results are based on flame photometry after removal of interfering Fe and Al by means of an ion exchange column of Amberlite I.R.A. 400 resin in the citrate form. After removal of all the Fe, Al, and Ti as oxinates by means of a continuous extractor, CaO and MgO were determined by titration using sodium ethylenediamine tetra-acetate. Calcein was used for the CaO and solochrome black for the CaO + MgO. P_2O_5 was determined by producing the molybdenum blue colour by reduction with ascorbic acid (J. Murphy and J. P. Riley, 1957). FeO was determined conventionally in the staurolite-free pelites but in the staurolite-bearing ones FeO was determined by a modification of Rowledge's method (1934, p. 165). Rowledge's method for determining FeO in refractory silicates is to fuse the sample with sodium metafluorborate flux in a pyrex tube which is sealed to prevent oxidation of the melt by atmospheric oxygen. With samples that have a substantial water content there is a risk that steam, formed from this water, will explode the sealed tube. To avoid sealing the tube a small piece of solid CO_2 was dropped into it on top of the rock sample and flux, and then the free end of the tube was connected by means of rubber tubing to a " T " piece, one end of which was open to the air and the other was connected to a flask filled with solid CO_2. The evolution of CO_2 from this flask prevented atmospheric oxidation. The sample tube was heated with an oxygen-compressed air-coal gas torch. H_2O+ and S (as SO_2) were determined using weighed absorption tubes and an electric furnace which ran at 1,150° C. (J. P. Riley, 1958). The accuracy of these methods will be the subject of a separate communication by Dr. J. P. Riley, but it can be said here that the accuracy is rather better than that obtained using classical methods of rock analysis.

The plagioclase compositions were obtained by measuring the maximum extinction angle ($X \wedge 010$) on the universal stage while the 2V of the staurolite was obtained by plotting its optic axes on a stereographic net.

The minerals were separated from the crushed rocks by means of an isodynamic separator. The resulting concentrates were repeatedly centrifuged in heavy liquids until their purity was not less than 99 per cent.

Pelites from South Connemara

Eight pelites have been analysed from south of the Connemara antiform and a garnet separated from one of them. With the exception of

TABLE 1

	B.L. 2096.	*B.L. 672.*	*B.L. 1714.*	*B.L. 734.*	*B.E. 708.*	*B.E. 558.*	*B.E. 811.*	*B.L. 124.*
SiO_2	48·16	42·58	46·13	44·08	51·60	42·64	45·30	47·50
Al_2O_3	23·35	27·39	23·62	26·79	21·50	31·45	23·62	23·85
TiO_2	1·68	1·34	1·35	1·77	1·59	1·24	2·15	2·00
Fe_2O_3	1·65	1·60	3·62	2·22	0·85	4·61	6·75	3·92
FeO	10·02	9·62	8·90	10·51	9·40	8·11	6·31	9·16
MgO	3·52	3·20	4·62	3·42	2·90	2·22	3·92	3·39
CaO	1·41	2·90	0·21	0·32	2·17	0·53	0·45	0·43
Na_2O	1·58	2·53	0·75	0·72	1·95	0·93	0·97	0·51
K_2O	3·94	4·73	6·31	4·74	3·38	4·84	5·41	3·69
P_2O_5	0·44	0·10	0·15	0·12	0·21	0·05	0·18	0·19
MnO	0·19	0·24	0·09	0·14	0·14	0·06	0·26	0·07
H_2O+	4·32	2·98	4·43	5·37	3·86	3·28	4·50	5·60
S	0·05	0·16	0·11	0·13	0·12	0·12	0·10	0·26
	100·31	99·37	100·29	100·33	99·67	100·08	99·92	100·57
Less O for S.	0·02	0·08	0·05	0·06	0·06	0·06	0·05	0·13
	100·29	99·29	100·24	100·27	99·61	100·02	99·87	100·44

NIGGLI NOS.								
si	141	109	129	125	161	116	129	143
al	40	42	39	45	40	50·5	40	42·5
fm	44	36	48	44	41	37	47	47
c	4	8	0·5	1	7	1·5	1	1·5
alk	12	14	13	10	13	11	12	9
ti	3·68	2·47	2·84	3·74	3·76	2·46	4·44	4·53
p	0·53	0·08	0·17	0·08	0·28	0·12	0·26	0·26
k	0·63	0·55	0·85	0·82	0·54	0·78	0·79	0·79
mg	0·35	0·36	0·40	0·32	0·33	0·24	0·35	0·35

B.L. 2096.—Biotite-sericite-quartz-garnet schist.
760 yd. on a bearing of 276° from the west point of Loughaunocary, 6 in. sheet 51, Co. Galway.

B.L. 672.—Biotite-andesine-sillimanite-garnet schist.
30 yd. S.W. of the lough with two islands in it and about 1 mile west of Loughaunemlagheask, 6 in. sheet 51, Co. Galway.

B.L. 1714.—Biotite-sericite-quartz-sillimanite schist.
150 yd. W.S.W. of the most western point of Loughaunemlagheask, 6 in. Sheet 51, Co. Galway.

B.L. 734.—Sericite-chlorite-garnet schist.
960 yd. E.S.E. of the south point of Wood's Lough, 6 in Sheet 51, Co. Galway.

B.E. 708.—Biotite-sericite-quartz-andesine schist.
½ mile on a bearing of 110° from Ballynahinch station, 6 in. sheet 50, Co. Galway.

B.E. 588.—Biotite-sericite-andalusite-andesine hornfels.
Roadside Quarry beside Owenmore River at bend in road 750 yd. downstream from the footbridge, 6 in. sheet 50, Co. Galway.

B.E. 811.—Sericite-chlorite-quartz-megnetite schist.
1½ mile on a bearing of 110° from Ballynahinch station, 6 in. sheet 50, Co. Galway.

B.L. 124.—Chlorite-sericite-quartz schist.
Seashore, western point of Errislannan Promontory, Curhownagh, 6 in. sheet 35, Co. Galway.

BE. 588 all the schists contained sillimanite before epifacial sericitization partially or completely destroyed it. This alteration process also incipiently or completely chloritized and sericitized the biotite and released Ti from it to form leucoxene. Text-fig. 1 shows the locations of the analysed samples and Table 1 gives the results of the chemical analyses together with the Niggli numbers of the rocks. The SiO_2 varies from 42 to 52 per cent, the Al_2O_3 from 21 to 32 per cent, and the total of $Fe_2O_3 + FeO$ from 10 to 13 per cent. Table 2 gives the Niggli katavariants which have been calculated, as far as is possible, to correspond with the modal analyses of the rocks as given in Table 3.

In all the katavariants the garnet has been calculated to the amount found in the mode and so that the composition is 85 per cent almandine and 15 per cent pyrope, the approximate composition found by analysis of garnet BE 707 (Table 8). If the katavariants are calculated using Niggli standard biotite and muscovite (Niggli, 1954, pp. 134–7) then there is a prominent deficiency in normative biotite compared with the modal biotite. This is because the biotite in these pelites contains considerably less than the $12(Fe^2 + Mg)$ atoms per 32 cations taken by Niggli. Therefore, in Table 2 the katavariant is calculated so that the normative and modal biotite volumes are equal. The Ti has also been calculated into the biotite and also any excess Fe^3. The ratio of Si/Al in the biotite has been calculated so as to make the modal and normative quartz values as near equal as possible, but always keeping the biotite composition within the limits given by Niggli (1954, p. 94). Clearly the composition of the biotite cannot be calculated accurately because the composition of the muscovite is unknown and in each norm except for BL 734 and BE 588 the muscovite has been calculated to Niggli's standard composition, viz. $[Si_{12}\ Al_4\ O_{40}\ (OH)_8 | Al_8]\ K_4$. This is the most aluminous muscovite possible. Although the precise composition of the biotite is unknown, some important deductions about its composition can be made. (1) The $Fe^2 + Mg$ usually = 7 to 9 atoms per 32 cations in the biotite. (2) The (Na + K) atoms usually total less than four in both the muscovite and the biotite. This may be due to slight loss of alkali from the rock during epifacial alteration of the biotite or alternatively the sericite formed from the sillimanite may still contain groups of relic sillimanite molecules. (3) Since in each norm except BE 588 there is too much An there must be some Ca in the micas. Either the CaO in analysis BE 588 is low or the modal plagioclase is high. (4) The $\frac{Fe^2}{Mg}$ ratio in the biotite varies from 1 to 1·7, a range which agrees with Heinrich's (1946, p. 844) conclusions about the compositions of biotites from mica schists.

TABLE 2.—NIGGLI KATAVARIANTS

	B.L. 2096.	*B.L. 672.*	*B.L. 1714.*	*B.L. 734.*	*B.E. 708.*	*B.E. 588.*	*B.E. 811.*	*B.L. 124.*	*RMS 100.*	*RMS 238.*	*RMS 231.*	*RMS 304.*	*RMS 305.*	*S 26/1.*	*RMS 315A.*	*RMS 308.*	*B. 481.*
Mt.	0·50	—	1·03	—	—	3·77	7·40	4·46	0·13	1·45	0·76	—	—	2·11	1·78	0·51	2·36
Pr.	0·10	0·45	0·27	0·36	0·27	0·23	0·27	0·71	0·27	1·03	0·54	0·52	—	0·79	0·29	0·27	0·36
Hm.	—	—	—	1·67	—	—	0·09	—	—	—	0·36	1·44	0·11	—	—	—	—
An.	4·71	14·71	—	—	10·61	2·33	1·20	1·20	1·30	—	4·09	2·34	1·79	1·60	7·68	3·80	5·06
Ab.	—	22·30	—	—	—	6·27	3·91	0·68	—	—	5·06	5·28	3·98	5·00	7·92	4·93	14·75
Or.	0·50	1·42	—	—	—	—	—	—	—	—	—	—	—	—	—	—	2·20
Cp.	0·89	0·01	0·29	0·12	0·30	0·12	0·42	0·41	0·45	0·12	0·41	0·29	0·29	0·15	0·60	0·30	0·15
Ru.	—	—	—	1·32	—	—	1·56	1·51	—	0·35	0·99	0·76	—	0·94	1·31	0·59	1·30
Pyp.	1·28	0·60	—	1·86	1·08	—	—	—	—	2·40	1·80	—	1·05	—	—	—	—
Alm.	7·21	3·40	—	10·62	6·12	—	—	—	7·80	9·63	7·18	3·14	1·75	1·80	3·80	3·00	—
Staur.	—	—	—	—	—	—	—	—	—	12·72	13·46	36·39	35·68[9]	23·90	2·00	8·40	—
Mg Bi	36·40[1]	46·30[2]	51·27[3]	—	32·60[5]	38·20[6]	—	—	5·70	3·98	10·24	8·12	13·39[10]	6·12	14·85	10·19	14·47
Fe Bi									—	4·46	9·76	4·00		3·20	17·72	12·31	16·31
Fe Ant	—	—	—	2·41	—	—	3·98	—	—	—	—	—	—	—	—	—	—
Mg Ant	—	—	—	2·41	—	—	6·34	—	—	—	—	—	—	—	—	—	—
Fe At	—	—	—	7·21	—	—	1·95	14·50	6·52	—	—	—	—	—	—	—	—
Mg At	—	—	—	8·18	—	—	4·97	12·68	0·55	0·56	—	—	0·48	—	—	—	—
K Ms	8·07	—	22·36	60·71[4]	8·00	20·60[7]	48·00	33·34	48·11[8]	40·50	22·71	13·07	12·54[11]	43·32[12]	10·46	28·77	18·72
Na Ms	20·61	—	—		18·40	—	7·05	5·80		6·77	13·46	8·58			8·80	7·89	—
Q	17·66	1·39	16·91	3·13	18·87	2·06	12·86	24·74	6·47	14·95	4·73	15·22	26·42	10·28	3·81	18·38	7·44
Cord.	—	—	—	—	—	0·40	—	—	—	—	—	—	—	—	—	—	—
And or Sil.	2·08	9·53	7·87	—	3·85	26·20	—	—	22·70	—	4·47	0·84	—	—	18·98	0·50	16·68

EXPLANATION TO TABLE 2

[1]$Bi_{sp} = [Si_{10}\,Al_6\,O_{40}\,(O,F,OH)_8|Ti_{1\cdot09}\,Fe^3_{0\cdot75}\,Al_{1\cdot95}\,Fe^2_{4\cdot85}\,Mg_{4\cdot10}]$
$(Na + K)_{3\cdot26}\,\frac{Fe}{Mg} = 1\cdot18$

[2]$Bi_{sp} = [Si_{10}\,Al_6\,O_{40}\,(O,F,OH)_8|Ti_{0\cdot63}\,Fe^3_{0\cdot79}\,Al_{2\cdot07}\,Fe_{4\cdot48}\,Mg_{3\cdot03}]$
$K_{3\cdot81}\,Na_{0\cdot19}\,\frac{Fe}{Mg} = 1\cdot48$

[3]$Bi_{sp} = [Si_{10}\,Al_6\,O_{40}\,(O,F,OH)_8|Ti_{0\cdot47}\,Fe^3_{1\cdot31}\,Al_{1\cdot71}\,Fe_{4\cdot30}\,Mg_{4\cdot16}]$
$K_{3\cdot91}\,Na_{0\cdot88}\,\frac{Fe}{Mg} = 1\cdot03$

[4]$Ms_{sp} = [Si_{14}\,Al_2\,O_{40}\,(O,F,OH)_8|Al_8]\,K_{2\cdot72}\,Na_{0\cdot60}\,Ca_{0\cdot11}$
[5]$Bi_{sp} = [Si_{12}\,Al_4\,O_{40}\,(O,F,OH)_8|Ti_{1\cdot16}\,Fe^3_{0\cdot62}\,Al_{0\cdot89}\,Fe^2_{3\cdot36}\,Mg_{3\cdot77}]$
$K_{3\cdot04}\,Na_{1\cdot07}\,\frac{Fe}{Mg} = 1\cdot42$

[6]$Bi_{sp} = [Si_{12}\,Al_4\,O_{40}\,(O,F,OH)_8|Ti_{0\cdot73}\,Fe^3_{0\cdot74}\,Al_{4\cdot50}\,Fe^2_{4\cdot47}\,Mg_{3\cdot63}]$
$K_{2\cdot57}\,Na_{0\cdot36}\,\frac{Fe}{Mg} = 1\cdot70$

[7]$Ms_{sp} = [Si_{13\cdot72}\,Al_{0\cdot27}\,O_{40}\,(O,F,OH)_8|Al_8]\,K_4$
[8]$Ms_{sp} = [Si_{16\cdot3}\,O_{40}\,(OH,F,O)_8|Ti_{0\cdot2}\,Fe^3_{0\cdot7}\,Al_{5\cdot2}]\,K_{4\cdot15}\,Na_{0\cdot5}$
RMS 238 also has 0·21 Na and 0·87 Ca not allocated to any mineral.

[9]$Staur_{sp}$ and [10]Bi_{sp} calculated to composition given in Table 8 while
[11]$Ms_{sp} = [Si_{14}\,Al_2\,O_{40}\,(O,F,OH)_8|Al_8]\,K_4$
RMS 305 has excess of 1·14 Na, 0·03 Ca, 0·12 K and 0·49 C.
Plagioclase is An_{31} and 0·74 Ilm has been calculated.

[12]$Ms_{sp} = [Si_{14}\,Al_2\,O_{40}\,(OH,O,F)_8|Al_8]\,K_{2\cdot63}\,Na_{1\cdot37}$. Also 0·78C calculated in S26/1. Plagioclase is An_{34}.

RMS 315A.—Bi has $\frac{Fe}{Mg} = 1\cdot2$ and 8·3(Fe + Mg) per 32 cations in biotite. This mica must also be extremely rich in Si and Al (because of excess And), and poor in K + Na. The Ms probably also has these characteristics. Plagioclase is An_{49}.

RMS 308.—Bi has $\frac{Fe}{Mg} = 1\cdot2$. Plagioclase is An_{44}.

B. 481.—Plagioclase is An_{26}.

TABLE 3.—MODAL ANALYSES

	B.L. 2096.	*B.L. 672.*	*B.L. 1714.*	*B.L. 734.*	*B.E. 708.*	*B.E. 588.*	*B.E. 811.*	*B.L. 124.*
Opaque	0·5	1·4	1·3	3·4	2·3	4·0	7·3	3·8
Plagioclase	4·1	33·3	0·7	—	10·6	8·6	—	—
Orthoclase	0·5	1·4	—	—	—	—	—	—
Biotite	36·4	46·3	51·7	—	32·6	38·2	—	—
Garnet	8·5	4·0	—	12·5	7·2	—	—	—
Chlorite	—	—	—	20·3	—	—	34·2	47·8
Sericite	28·7	—	22·4	62·2	26·4	20·6	49·2	36·3
Quartz	21·0	0·5	15·9	1·6	20·6	1·8	9·3	11·8
Sillimanite	—	13·0	8·0	—	—	—	—	—
Andalusite	—	—	—	—	—	26·2	—	—
Apatite	0·3	—	—	—	0·3	—	—	0·3
Tourmaline	—	—	—	—	—	0·2	—	—
Cordierite	—	—	—	—	—	0·4	—	—
Composition of Plagioclase	An_{30}	An_{37}	nd	—	An_{31}	An_{39}	An_{30}	—

Pelites from North Connemara

Five pelites from north Connemara antiform have been analysed (Table 4). RMS 100 contains a little sillimanite but the other four are staurolite-garnet bearing rocks. Some sericitization and chloritization of the biotite in these rocks is common and the staurolite is occasionally partly replaced by shimmer aggregates of mica. Except for RMS 305 most of the compositions of the constituent minerals are unknown and so little further mineralogical information can be obtained from the katavariants (Table 2). Both the staurolite and the biotite in RMS 305 have been analysed (Table 8) and so the katavariant has been calculated to the actual composition and modal volume of staurolite and biotite. It can then be seen that the katavariant does not differ appreciably from the mode, there being only a slight excess of sodium in the norm. When the MnO content of rock RMS 305 and the MnO content of its constituent staurolite and biotite are compared, it is evident that there must be a prominent concentration of MnO in the garnet of the rock.

Broadly, the plots of Niggli numbers (Text-figs. 2 and 3) from both sides of the antiform show similar compositions. The range of *si*, *alk*, *c*, and *k* numbers is the same for both sets of rocks. Since the greatest, and first, change that occurred during the metasomatism of the aureoles of the ultrabasic intrusions was a fall in the silica and alkalis (details to be published) it is concluded that this metasomatism has not affected the rocks outside the aureoles in the south. There are, however, rather higher *al* and lower *fm* and *mg* figures in the northern rocks compared with the southern ones. It is difficult to see why this is so unless it is an original sedimentation difference. The high *al* and lower *fm* and *mg* values are reflected in the high staurolite contents of some of the northern rocks.

Pelites from Eastern Connemara

Four pelites from eastern Connemara have been chemically and modally analysed and the results, together with the katavariants, are given in Tables 6, 7, and 2. RMS 308 and B 481 contain sillimanite, the latter is also rich in pinitized cordierite while RMS 315A contains andalusite, staurolite, and garnet. Neither RMS 315A nor B 481 are within several miles of a basic or ultrabasic intrusion. As the mineral assemblages are rather complex and most of the mineral compositions are unknown little mineralogical information can be gained from the katavariants. The plots of Niggli numbers (Text-figs. 2 and 3) show little significant variation compared with the other Connemara pelites. There is a tendency to fall between the rocks from south Connemara and north Connemara on the *si*/*fm*, *si*/*al*, and *k*/*mg* plots.

TABLE 4

	RMS 100.	*RMS 238.*	*RMS 231.*	*RMS 304.*	*RMS 305.*
SiO_2	49·73	48·00	41·88	46·38	52·53
Al_2O_3	27·50	27·83	29·20	30·37	26·76
TiO_2	0·39	0·46	1·38	1·03	1·02
Fe_2O_3	1·66	1·40	1·15	1·98	1·45
FeO	6·89	9·36	10·76	9·74	7·86
MgO	1·61	1·95	3·09	2·09	2·31
CaO	0·53	0·90	0·98	0·59	0·61
Na_2O	0·46	0·62	1·56	1·42	1·25
K_2O	6·26	5·52	4·63	2·40	2·71
P_2O_5	0·18	0·09	0·23	0·16	0·17
MnO	0·08	0·23	0·16	0·15	0·18
H_2O+	4·20	3·19	4·45	3·13	2·69
S	0·10	0·40	0·21	0·18	0·04
	99·59	99·95	99·68	99·62	99·58
Less O for S	0·05	0·20	0·10	0·09	0·02
	99·54	99·75	99·58	99·53	99·56
NIGGLI NOS.					
si	155	143	112	135	172
al	53	48·5	46	52	51·5
fm	31	35·5	39	37·5	37
c	2	3	3	2	2
alk	14	13	12	8·5	9·5
ti	0·98	1·07	2·73	2·28	2·36
p	0·28	0·13	0·24	0·18	0·30
k	0·90	0·86	0·66	0·52	0·59
mg	0·25	0·24	0·32	0·24	0·31

RMS 100—Muscovite-sillimanite-garnet-biotite schist.
495 yd. E.N.E. of Mullaghglass House, 6 in. sheet 10, Co. Galway.

RMS 238—Muscovite-staurolite-garnet-quartz-biotite schist.
550 yd. N.W. of Rinvyle Church, 6 in. sheet 10, Co. Galway.

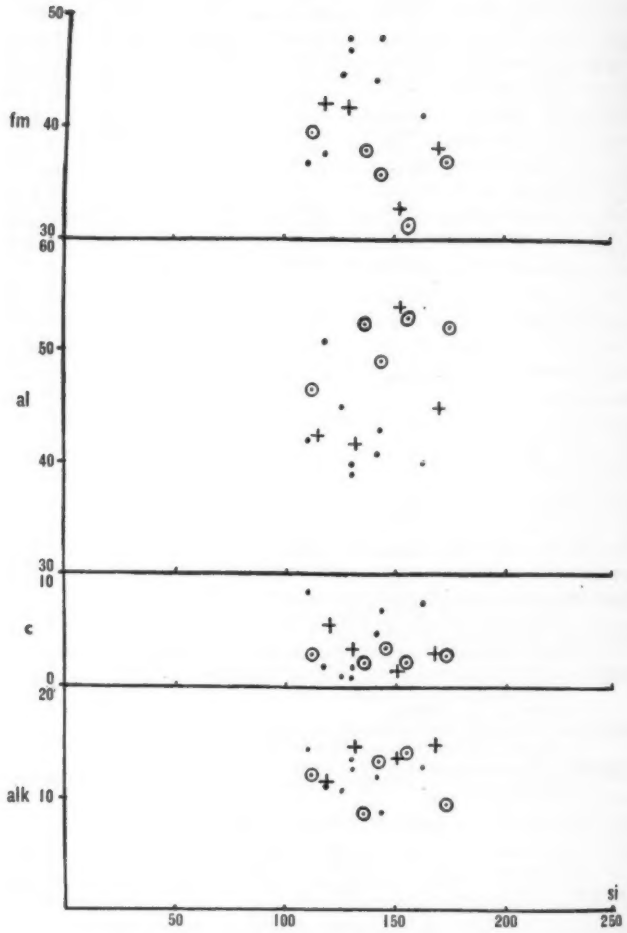
RMS 231—Muscovite-biotite-staurolite-andesine-garnet schist.
Rushyhaughtely, Barnaderg Bay, east extremity of exposure, 6 in. sheet 23, Co. Galway.

RMS 304—Staurolite-muscovite-quartz-biotite-garnet schist.
410 yd. S.E. of Rinvyle Church, 6 in. sheet 10, Co. Galway.

RMS 305—Staurolite-quartz-biotite-muscovite-garnet schist.
About ½ mile W. of Rinvyle Church, 6 in. sheet 10, Co. Galway.

TABLE 5.—MODAL ANALYSES

	RMS 100.	*RMS 238.*	*RMS 231.*	*RMS 304.*	*RMS 305.*
Opaque	0·4	1·1	1·0	1·35	0·9
Biotite	5·7	8·5	28·4	10·0	13·4
Muscovite	47·0	48·3	30·6	20·2	12·6
Garnet	7·8	12·0	9·0	3·1	2·8
Staurolite	—	12·7	13·5	36·3	35·7
Quartz	6·4	11·5	4·0	16·3	25·1
Plagioclase	0·7	—	12·0	8·1	5·8
Chlorite	8·9	5·9	1·3	4·5	3·6
Sillimanite	22·7	—	—	—	—
Tourmaline	0·4	—	0·2	—	0·1
Composition of Plagioclase	nd	nd	An_{32}	An_{31}	An_{31}



TEXT-FIG. 2.—Plots of Niggli nos. Connemara pelites.

● South Connemara pelites. ⊙ North Connemara pelites.
+ East Connemara pelites.

TABLE 6

	S 26/1.	*RMS 315A.*	*RMS 308.*	*B 481.*
SiO_2	47·52	41·06	51·95	45·60
Al_2O_3	28·74	27·36	23·80	24·53
TiO_2	1·26	1·78	0·83	1·77
Fe_2O_3	1·94	1·63	0·72	2·51
FeO	7·45	10·75	8·60	8·48
MgO	1·57	3·79	2·65	3·69
CaO	0·37	1·83	0·87	0·98
Na_2O	1·65	1·48	1·12	1·57
K_2O	4·20	4·47	5·56	5·53
P_2O_5	0·10	0·28	0·22	0·10
MnO	0·15	0·23	0·22	0·10
H_2O+	4·38	4·81	3·20	4·50
S	0·30	0·12	0·12	0·15
	99·63	99·59	99·86	99·51
Less O for S	0·15	0·06	0·06	0·07
	99·48	99·53	99·80	99·44
NIGGLI NOS.				
si	150	117	166	129
al	53·5	42	45	41·5
fm	32	42	38	41·5
c	1	5	3	3
alk	13·5	11	15	14
ti	3·01	3·45	1·92	3·75
p	0·09	0·31	0·29	0·09
k	0·63	0·66	0·76	0·70
mg	0·23	0·35	0·33	0·38

S 26/1.—Muscovite-staurolite-biotite-quartz-garnet schist.
400 yd. S.W. of Ballard, N. of Cornamona Bay, Lough Corrib, 6″ sheet 27, Co. Galway.

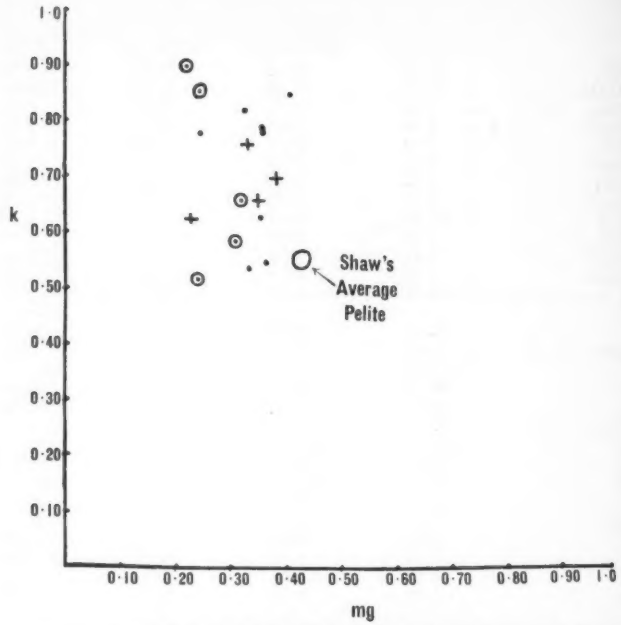
RMS 315A.—Biotite - muscovite - oligclase - andalusite - staurolite - garnet schist.
Roadside quarry at BM. 193·4, Claggan, 6 in. sheet 39, Co. Galway.

RMS 308.—Muscovite-biotite-quartz-staurolite-garnet schist.
1,600 yd. on a bearing of 283° from Maam Hotel, 6 in. sheet 25, Co. Galway.

B 481.—Pinitized cordierite-biotite-oligoclase andesine-sillimanite schist.
By the second t of Lettercraff on 6 in. sheet 54, Co. Galway.

TABLE 7.—MODAL ANALYSES

	S 26/1.	*RMS 315A.*	*RMS 308.*	*B 481.*
Biotite	10·9	47·0	32·6	31·6
Chlorite	5·9	—	—	—
Muscovite	39·7	25·8	34·2	2·0
Staurolite	23·9	2·0	8·4	—
Garnet	1·8	3·8	3·0	—
Quartz	8·8	0·4	17·9	—
Plagioclase	6·6	15·6	2·7	22·0
Andalusite	—	4·3	—	—
Sillimanite	—	—	0·5	5·1
Pinite	—	—	—	35·0
Orthoclase	—	—	—	2·2
Opaque	2·2	1·1	0·6	2·2
Tourmaline	0·2	—	—	—
Composition of Plagioclase	c.An_{22}	An_{18}	nd	An_{29}



TEXT-FIG. 3.—Plots of Niggli k and mg ratios, Connemara pelites.
● South Connemara pelites.
○ North Connemara pelites.
+ East Connemara pelites.

MINERAL ANALYSES

The analysed garnet, BE 707, is almandine rich (Table 8) and its composition is fairly typical of garnets from pelites (W. I. Wright, 1938, p. 447). Bernard Evans has determined the cell size and refractive index of six garnets from pelites in south Connemara and the results were practically identical with those given in Table 8. Because of this constancy of physical constants of the garnets it has been assumed in Table 2 that all the garnets from south Connemara pelites are the same in composition as the analysed garnet. If the data given by Skinner (1956, p. 428) are used to calculate the R.I. and the cell size from the chemical composition, both the R.I. (1·811) and the cell size (11·51Å) agree with the actual values (1·809 ± 0·002 and 11·526 ± 0·003Å). According to Miyashiro (1953, p. 179) the high almandine content combined with the low spessartite and moderate pyrope content, suggests metamorphism of fairly high amphibolite facies, a

view supported by the widespread abundant sillimanite in south Connemara.

Except for its high water content the analysed staurolite is of similar composition to those recently studied by A. Juurinen (1956) who has shown that the $Fe^3 + Fe^2$ atomic ratio in the unit cell (48 O) of ferroan (i.e. normal) staurolite can vary from 2·85 to 3·43. RMS 305 contains 3·27 $Fe^3 + Fe^2$ in the unit cell. The high water content may be partly due to the existence of some liquid inclusions within the staurolite.

TABLE 8.—MINERAL ANALYSES

	Garnet BE 707.	*RMS. Staurolite*	*305. Biotite*
SiO_2	37·28	27·36	34·35
Al_2O_3	21·15	52·12	21·20
TiO_2	0·25	0·73	1·60
Fe_2O_3	0·83	1·11	3·05
FeO	34·45	13·09	19·70
MgO	4·36	2·44	7·90
CaO	0·43	0·29	0·28
Na_2O	0·13	0·10	0·60
K_2O	0·19	0·34	7·56
P_2O_5	0·05	0·10	0·07
MnO	0·94	0·10	0·07
H_2O	0·41	2·47	4·10
S	—	0·01	0·01
	100·47	100·16	100·49

Staurolite (48 O) RMS 305.				
Si	7·59	7·59		
Al	17·10		17·48	
Ti	0·15			
Fe^3	0·23			
Fe^2	3·04			
Mg	1·00	4·14		
Ca	0·08			
Mn	0·02			
Na	0·05			
K	0·12			
P	0·02			
H	4·57			
$2V_x = 84°$				

Biotite 48(O + OH) RMS 305.		
Si	10·32	16·00
Al	5·68	
Al	1·84	
Ti	0·36	2·88
Fe^3	0·68	
Fe^2	4·94	
Mg	3·54	8·52
Mn	0·04	
K	2·90	
Na	0·34	3·34
Ca	0·10	
OH	8·22	
O	39·78	
Ny = Nz =	1·644 ± 0·003	

	Garnet BE 707.	*Recalculated to 100 per cent.*
Almandine	79·65	81·61
Pyrope	14·63	15·00
Spessartite	2·14	2·19
Andradite	1·17	1·20

N = 1·809 ± 0·002
a = 11·526 ± 0·003 Å

BE. 707 came from 130 yd. at a bearing of 295° from BE. 708 (Table 1).

These could not be completely removed despite constant grinding and centrifuging in heavy liquid. For this reason the specific gravity of the mineral has not been determined. It is noteworthy that there is appreciable alkali in the staurolite although most of the previous analyses of staurolites do not include determinations of Na_2O and K_2O.

Biotite RMS 305, although falling within the range of compositions of normal biotites from mica schists (Heinrich, 1946, p. 843) is fairly rich in FeO. It is deficient in alkali and fairly rich in water, suggesting perhaps, that although all the microscopically visible chlorite was removed before analysis, the biotite may nevertheless be incipiently altered. N. J. Snelling (1957, p. 302) has recently described biotites of very similar composition from the Stonehaven coast but he does not

comment on the alkali deficiency. The ratios of Si/Al and of Fe^2/Mg in biotite RMS 305 are similar to those deduced for the biotites from south Connemara (Table 2).

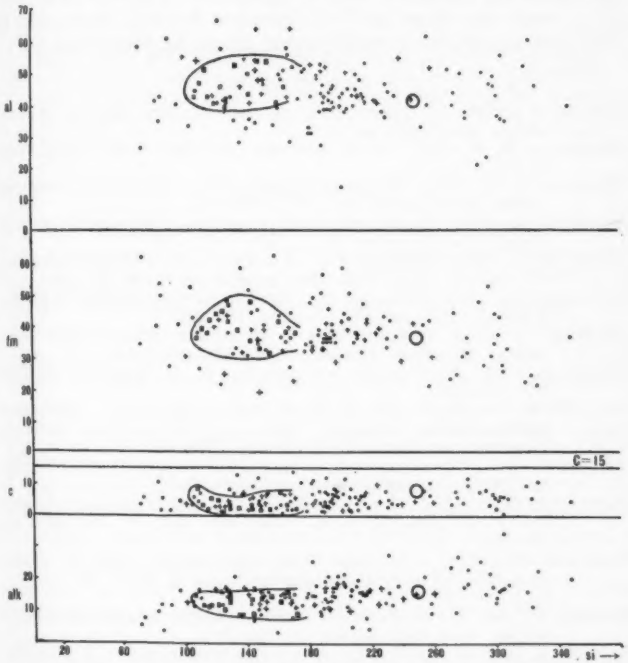
Conclusions and Discussion

The 17 analysed pelites from different parts of Connemara have roughly similar compositions. This indicates that the desilication and dealkalization which occurred in the aureoles of the ultrabasic intrusions in south Connemara, did not extend appreciably outside the aureoles. It is suggested that the slightly higher *al* and lower *fm* and *mg* values found north of the Connemara antiform compared with those to the south, are the result of an original sedimentation difference because the variations are not related to *si* or *alk* variation.

Text-fig. 4 is a plot of the Niggli numbers of 30 Scottish metapelites (mostly schists), 17 Connemara metapelites (partially ringed), and 94 metapelites from the Alps. The Scottish plots are mostly taken from N. J. Snelling (1957, p. 301), D. H. Williamson (1953, p. 359), H. H. Read (1931, p. 40), and the memoirs of the Geological Survey. The Alpine plots are mostly taken from P. Niggli, F. de Quervain, and R. U. Winterhalter (1930). No rocks which were described as gneisses or injected or which had more than 70 per cent SiO_2 or a Niggli *c* number greater than 15 have been plotted. Thus migmatitic rocks, siliceous granulites, and calcareous rocks have been excluded as they are not relevant to the discussion. Included, however, is D. M. Shaw's statistically computed (from 155 analyses) "average pelite" (D. M. Shaw, 1956, p. 928). Compared with Shaw's average pelite and many pelites in the literature much of the pelite in Connemara is rather poor in silica, but the *al*, *fm*, *c*, and *alk* numbers are normal. There is, however, in addition even more semipelite and siliceous granulite in Connemara, though neither of these types is dealt with in this account and so the ring around the Connemara plots in Text-fig. 4 has not been completely closed. While there is no difficulty in finding comparable silica-poor metapelite analyses (e.g. Snelling, 1957, p. 301; A. Juurinen, 1956, p. 45), they are very uncommon and as Text-fig. 4 shows, there are only eight analyses plotted which are more deficient in silica than the most silica-poor Connemara pelites. Some of these eight are rather peculiar; one, for example, is magnetite-rich.

It is, however, at present impossible to deduce much of value by comparing Connemara pelites with those from elsewhere, because comparisons between pelites from different areas are complicated by different sampling techniques and by the absence of a precise terminology for pelite and semipelite. What has often been called pelite (e.g. Read, 1931, p. 148, SiO_2 *c.* 60 per cent) might be called semipelite by other workers to distinguish it from pelites which contain less than

50 per cent SiO_2. The distinction ought to be made at some agreed *si* figure. Text-fig. 4 does demonstrate that the pelite-semipelite series can be regarded as being made of variable amounts of quartz plus



TEXT-FIG. 4.—Plots of Niggli nos. of metamorphosed pelites and semi-pelites.

● Pelites from the Alps.
+ ,, ,, Scotland (including Shetland).
□ ,, ,, Connemara (partially ringed).
○ Shaw's average pelite.

another end member which has roughly constant *al*, *alk*, *c*, and *fm* numbers.

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Pelagic Foraminifera in the Tertiary of Victoria

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Abstract

A sequence of eleven faunal units characterized by pelagic foraminifera and embodying thirteen significant events has been recognized in the Tertiary of Victoria. They form a continuous sequence from the Upper Eocene to the Middle Miocene. Some of these events have been recognized in the same order in New Zealand, Europe, North America, the Caribbean region, and Saipan.

Introduction

THE Tertiary rocks of Victoria have been deposited in several epicontinental basins. Marine sedimentation in these basins has been practically continuous from the Upper Eocene to the Pliocene although their detailed histories have been somewhat different. Only in the deeper parts of the basins does the total thickness of Tertiary rocks exceed 3,000 feet in any one section. At most places it is considerably less and nowhere is the full sequence exposed continuously. These deposits have been little disturbed, but the whole region has been uplifted since the Pliocene and erosion has removed the younger formations over wide areas.

The majority of outcrops expose sediments of the peripheral belts of these basins and a wide variety of lithological types is presented, with clays, marls, and limestones predominating. The correlation of short exposed sequences and small outcrops of diverse facies with one another and with boreholes in the deeper parts of the basins has given rise in the past to much difference of opinion as to their age and correlation.

For some years the writer has been working on foraminifera from these rocks, seeking a practical basis for detailed correlation. South-Eastern Australia lies well outside the Tethyan belt and larger foraminifera are of little value for local subdivision and correlation—in fact, they appear only during one short interval and then only in appropriate facies. The principal genera here are *Cycloclypeus* and trybliolepidine *Lepidocyclina*. (See Faunal Unit 9, below.)

In the course of this work, pelagic foraminifera have been found to be most useful, because of their occurrence in different sedimentary environments which limit the distribution of some otherwise important benthonic species. Nevertheless, local variation of environment has some effect and pelagic forms are not equally abundant everywhere.

The writer has recognized a sequence of eleven associations of foraminifera ranging in age from Upper Eocene to Middle Miocene. Younger Tertiary rocks have not yet been examined fully.

The eleven associations are described here as "Faunal Units" because it is not yet desirable to give them the formal status of zones. To do this would imply that they had been more fully defined in terms of their component species and that their stratigraphical occurrence had been more widely traced than it has been to date. The detailed basis of these conclusions is published elsewhere (Carter, 1958).

The present paper represents an interim summary of a lengthy project. It is presented in the hope that the results so far obtained will be of interest to other workers both in Australia and abroad.

The significant species and their relative ranges, on which the units are based, are shown in Table 1.

Faunal Units

Faunal Unit 1.

A subspecies of *Hantkenina alabamensis* Cushman is restricted to this unit and its important associates are *Globigerinoides index* Finlay and *Globigerina linaperta* Finlay.

Faunal Unit 2.

The most significant species here is *Globigerinoides index*, which does not range above the top of this unit. The top of the Eocene is considered to coincide with the top of the range of *G. index* in New Zealand (Finlay and Marwick, 1947), and in other areas (Grimsdale, 1951; Beckmann, 1954). The highest occurrence of *Globigerinella micra* (Cole) is just below the top of Unit 2. *Globigerina linaperta* occurs throughout this unit and ranges higher. *Astrononion* occurs in this unit, therefore it ranges lower in the Tertiary than generally accepted.

Faunal Unit 3.

The pelagic fauna is dominated by a form of *Globigerina linaperta* with swollen chambers. The assemblage of Unit 3 is similar to that of Units 1 and 2 and is distinguished more by the absence of species restricted to these older units than by the appearance of "younger" species. *Globigerina linaperta* ranges higher than *Globigerinoides index* in Victoria, while in New Zealand the reverse is the case. However, it has been reported by Finlay (1939, p. 125) that *Globigerina linaperta* has a tendency to develop swollen chambers in the upper part of its range in New Zealand and this is also the case in Victoria. *Victoriella plecte* (Chapman), a benthonic species which has been prominent in Australian literature, makes its first appearance in this unit.

Faunal Unit 4.

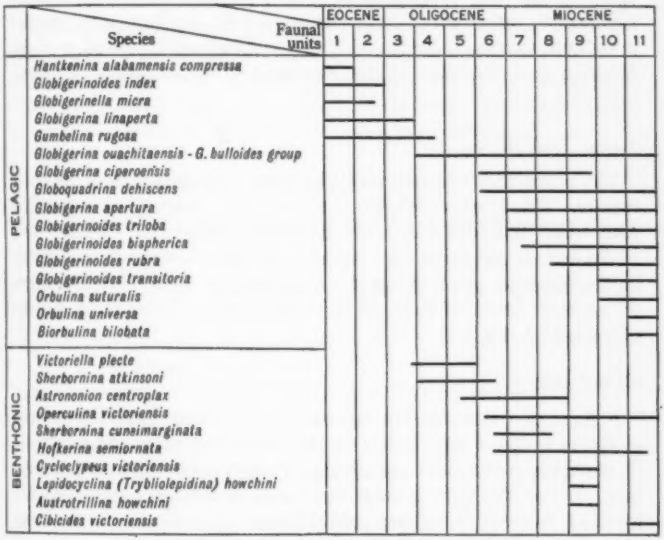
The disappearance of *G. linaperta* and its replacement by a species

of *Globigerina* comparable with *G. ouachitaensis* Howe and Wallace is the important feature of this unit. This form may be responsible for all Lower Tertiary records of *G. bulloides* d'Orbigny, but further study and comparison with topotypes is required. *Sherbornina atkinsoni* Chapman makes its first appearance in this unit.

Faunal Unit 5.

The pelagic foraminifera show no significant change from the preceding unit, but several important benthonic species make their

TABLE 1



first appearances here. The most notable of these is *Astrononion centroplax* Carter. *Victoriella plecte* does not occur higher than this unit. *Sherbornina atkinsoni* is present.

Faunal Unit 6.

Important pelagic species appearing here are *Globoquadrina dehiscens* (Chapman, Parr and Collins) and *Globigerina ciperoensis* Bolli. The latter species appears to be an offshoot from the *G. ouachitaensis–G. bulloides* lineage. Among the benthonic species, *Astrononion centroplax* continues, while *Operculina victoriensis* Chapman and Parr,

Hofkerina semiornata (Howchin), and *Sherbornina cuneimarginata* Wade make their appearance. *S. atkinsoni* is present in the lower part of this unit.

Faunal Unit 7.

The appearance of *Globigerinoides triloba* (Reuss) characterizes this unit, within which it gives rise to *G. bispherica* Todd (see Blow, 1956). *Globigerina apertura* Cushman, apparently another derivative from the *G. ouachitaensis–G. bulloides* lineage, makes its appearance in this unit.

It is noteworthy that in Victoria (and also in New Zealand—Hornibrook, 1958) *Globoquadrina dehiscens* makes its first appearance significantly earlier than *Globigerinoides triloba.* In Europe the reverse is the case (Drooger, 1956). This unit corresponds to the base of the Miocene (i.e. the base of the Aquitanian) as defined by Drooger (loc. cit.).

Faunal Unit 8.

The appearance of *Globigerinoides rubra* d'Orbigny is here the chief feature. This species probably evolved from a form of *G. bispherica* with three apertures along the equatorial suture. *G. triloba* and *G. bispherica* continue through this unit. Typical *Astrononion centroplax* does not survive this unit but it is succeeded by a more involute form with smaller apertural flaps, which rarely occurs with the index species of Faunal Unit 9.

Faunal Unit 9.

A form of *Globigerinoides triloba* with two large arched apertures at the base of the last chamber is the most distinctive pelagic form. *G. bispherica* is abundant and *Globigerina ciperoensis* is present, though rare. Within this unit, suitable facies contain *Lepidocyclina* (*Tryblio-lepidina*) *howchini* Chapman and Crespin, *Cycloclypeus victoriensis* Crespin (cf. *C. posteidae* Tan), *Austrotrillina howchini* (Schlumberger), and certain other restricted benthonic species.

The *Lepidocyclina howchini* populations display a range of eight to twenty nepionic spirals and the nepionic chambers of *Cycloclypeus victoriensis* have a maximum frequency of eight. These stages of morphogenesis correspond with those occurring in the uppermost Burdigalian or basal Vindobonian (cf. Tan, 1932, Table 3; Mohler, 1946, p. 307; Renz and Küpper, 1946, p. 322 and Table 18).

Faunal Unit 10.

Globigerinoides transitoria Blow and *Orbulina suturalis* Bronnimann

characterize this unit. The ranges of these species are incompletely known because it has not yet been possible to study beds containing them in stratigraphical continuity with both older and younger strata.

Faunal Unit 11.

The appearance of *Orbulina universa* d'Orbigny characterizes this unit. *Biorbulina bilobata* (d'Orbigny) makes its first appearance, as also does a large, distinctive benthonic species *Cibicides victoriensis* Chapman, Parr and Collins. In Europe, Drooger (1956) has shown that the first appearance of *Orbulina universa* is in the Middle Miocene (Tortonian).

Satisfactory indices of younger faunal units have not yet been recognized. The writer is at present working on Upper Tertiary sequences in Gippsland, where the faunas are strongly influenced by environment and pelagic species are comparatively rare. It is hoped to extend this sequence of faunal units at a later date.

Local Sequence of Events

From these Victorian data, the following sequence of events is established:—

(*a*) Association of *Hantkenina alabamensis* and *Globigerinoides index.*
(*b*) Occurrence of *Globigerinoides index* without *Hantkenina alabamensis.*
(*c*) Appearance of *Globigerina* sp. of the *G. ouachitaensis-G. bulloides* group.
(*d*) Appearance of *Globigerina ciperoensis.*
(*e*) Appearance of *Globoquadrina dehiscens.*
(*f*.1) Appearance of *Globigerinoides triloba.*
(*f*.2) Appearance of *Globigerina apertura.*
(*g*) Appearance of *Globigerinoides bispherica.*
(*h*) Appearance of *Globigerinoides rubra.*
(*i*.1) Appearance of *Globigerinoides transitoria.*
(*i*.2) Appearance of *Orbulina suturalis.*
(*j*.1) Appearance of *Orbulina universa.*
(*j*.2) Appearance of *Biorbulina bilobata.*

The index letters are introduced purely for convenience. Indices such as (*f*.1) and (*f*.2) are used to indicate separate parts of one event which, for the purposes of the following discussion, may be considered contemporaneous.

Comparison with Other Areas

The writer has observed in the faunal distribution charts and other data of several authors, some of the above events occurring in the same order. It has also been noticed that the Victorian Tertiary lacks many species such as *Globigerina globularis, G. dissimilis, Globigerinatella insueta* and the *Globorotalia fohsi* group which are zonal indices in the Caribbean region and also occur in Europe. This adds weight to Grimsdale's suggestion (1951, p. 464) that some species will have wider geographical ranges than others and consequently be more valuable in long-range correlation.

It is suggested that some of the species indicated in the above sequence of events may belong to this category. The following observations support this view:—

New Zealand.—In New Zealand, geographically the closest region for which information is available, ten of the above events can be recognized from data given by Finlay and Marwick (1940, 1947) and Hornibrook (1953, 1958). The order is as follows:—

*a, b, c, e, f.*2, *f.*1, *g, i.*2, *j.*1, *h*

Europe.—The information presented by Drooger (1956) reveals the following sequence:—

*c, d, f.*1, *e, g, i.*2, *j.*1

Although this compares well with the Victorian sequence, the inversion of events *e* and *f.*1 calls for wider checking of the relative order of appearance of *Globoquadrina dehiscens* and *Globigerinoides triloba.*

North America.—The following events are contained in data presented by Grimsdale (1951, p. 466), assuming that his record of *Globigerina concinna* in the Oligocene refers to *G. ciperoensis* (see Bolli, 1951):—

*a, d, e, f.*1

Caribbean Region.—Beckmann (1954) and Blow (1956) present data from the Caribbean region, the former dealing with the Eocene-Oligocene sequence of Barbados and the latter with a younger (Oligocene–Miocene) sequence in Trinidad. Combining information from both papers and taking Beckmann's record of *Globigerina concinna* to refer to *G. ciperoensis* (see Bolli, 1951), the following sequence of events is deduced:—

*a, b, c, d, f.*1, *g, i.*1, *j.*2, *i.*2, *j.*1

In this region, the appearance of *Biorbulina bilobata* is apparently earlier than in Victoria.

Saipan.—The following events can be recognized in the distribution chart of Todd, Cloud, Low and Schmidt (1954, p. 675).

*g, i.*2, *j.*1

Conclusions

From the above it will be seen that there is a general correspondence between the sequences of events in all these regions. The minor discrepancies which still exist will probably be resolved by future work. This paper supports the contention that some, at least, of the events affecting pelagic foraminifera were world-wide and contemporaneous.

The writer believes that the sequence of first appearances of pelagic foraminifera will eventually form the basis for intercontinental correlation of Tertiary rocks and a reliable foundation for Tertiary geochronology.

Acknowledgments

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GEOLOGICAL SURVEY OF VICTORIA,
MINES DEPARTMENT,
MELBOURNE, C. 2, AUSTRALIA.

The Lower Middle Hecla Hoek Rocks of Ny Friesland, Spitsbergen

By C. B. Wilson

(PLATES VII–VIII)

Abstract

This paper gives details of part of the Hecla Hoek Succession already outlined (Harland and Wilson, 1956). Field work in 1956 and 1957 in general confirmed the succession, and this account includes the results of the later work. A large-scale repetition of a sedimentary cycle is demonstrated, and the relationship with equivalent rocks in Nordaustlandet is discussed.

I. Introduction

THE Lower Middle Hecla Hoek rocks were defined in Ny Friesland on the basis of field work done in 1949, 1951, 1953, and 1955 and a summary of the succession was given as then found (Harland and Wilson, 1956) as well as a correlation with the published work of Odell (1927), Fairbairn (1933), Kulling (1934), and Fleming and Edmonds (1942), all of whom included these rocks in their descriptions. The Lower Middle Hecla Hoek rocks are the approximate equivalents of the Lower Murchison Bay Formation of Nordaustlandet (Kulling, 1932).

This paper gives an account of the rocks based on field work as follows. On the Cambridge Spitsbergen Expedition, 1949, outcrops in upper Gipsdalen, Nordenskiöldbreen, and southern Veteranen were visited (Harland, 1952). The Cambridge party of the Oxford and Cambridge Spitsbergen Expedition, 1951, established a centre camp in mid-Veteranen from which outcrops on either side of Veteranen south of Kortfjellet were investigated as well as the length of Chydeniusbreen (Harland and Hollin, 1953). The author accompanied the British Spitsbergen Expedition, 1952 (Bayly, 1953), whose object included the investigation of the Grusdievbreen and Oxfordbreen area. In 1955 I re-examined the mid-Veteranen sections and also briefly traversed sections around Heclahuken and Dunérbreen. In 1956 I investigated the Fakse area, Chydeniusbreen, and Polarisbreen and surveyed northern Veteranen and Glintbreen during 1957.

The most satisfactory outcrops of the Lower Middle Hecla Hoek rocks occur in the Fakse area and Veteranen in central Ny Friesland. North Ny Friesland is tectonically disturbed and imperfectly understood, and south Ny Friesland contains only small and widely scattered outcrops many of which remain unrelated. The best single exposure is that of Faksevågen, previously visited by de Geer and later by Kulling (1934), where all but the lowermost beds are available. I was able to traverse this section from above where the rocks are more

continuous, and my section is compared with Kulling's in Text-fig. 4, which gives a stratigraphical summary and correlation table. Although this area was not visited until after the succession had been built up from further south (Harland and Wilson, 1956), the original subdivisions apply with only slight modification to the Fakse area and also, in its broader outlines at least, to the remainder of Ny Friesland, so that the same terminology is used throughout. The distribution of the relevant rocks, together with place names mentioned in the text, are shown in Text-figs. 1 and 2 and the stratigraphy is summarized in Text-fig. 4 and Table 1.

II. The Lower Boundary

The stratigraphical nature of the boundary between the Lower Hecla Hoek (" western schists and gneisses ") and the Middle Hecla Hoek to the east has already been argued (Harland and Wilson, 1956) and related to earlier views. However, further exposures of the contact have since been visited, and the stratigraphical evidence is re-stated.

The boundary is exposed in at least six localities—from north to south: Sorgfjorden, Dunérbreen, Skinfaksebreen, northern Veteranen, mid Veteranen, and Terrierfjellet. Only in Terrierfjellet and northern Veteranen is there any evidence of structural irregularity at the contact; in the latter the basal 100 m. of the Veteranen Limestones are strongly brecciated with calcite veining, and the limestone strata contorted against a narrow gully which may mark the line of contact. However, the stratigraphy corresponds so closely with that of Skinfaksebreen and mid-Veteranen, where the strata show every sign of conformity, that such a fault is not likely to be of great throw. The Terrierfjellet fault is probably of a similar nature. The metamorphic grade is always transitional across the boundary, though sometimes, as in Dunérbreen, this transition appears to be rather rapid. The biotite-chlorite isograd does not precisely follow the boundary, and lies within the Planetfjella Schists in northern Veteranen and Skinfaksebreen, where the topmost " schists " consist of black phyllites (not dissimilar from the greywacke shales of the Veteranen Series), and the Veteranen Limestones have their fullest development. On the other hand, in Dunérbreen, mid-Veteranen, and southern Ny Friesland this isograd lies up to two miles east of the boundary, and the Limestones are strongly sheared and very thin. This is probably

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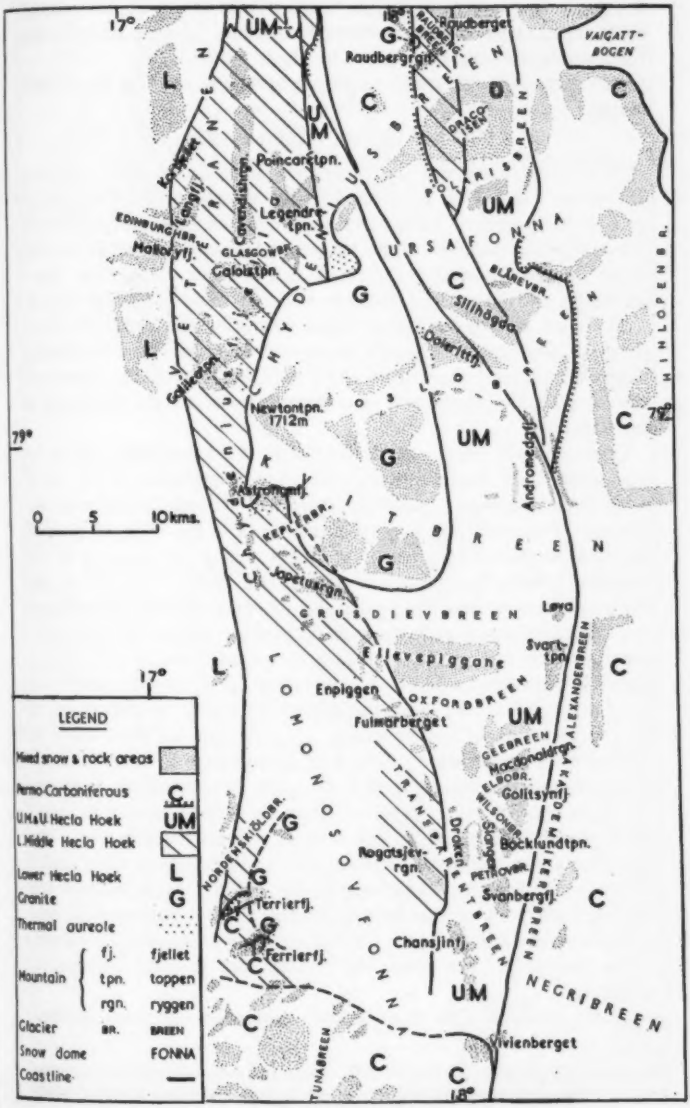
Text-fig. 1.—Sketch-map (1 : 500,000) of south-eastern Ny Friesland showing the distribution of the main rock groups and place-names referred to in the text. This is based on a more detailed topographical map of the area (compiled by Mr. Harland and to be published by the Royal Geographical Society) and a diagrammatic geological map of Ny Friesland (Harland, MS., Plate I).


17°
18°
79°
Raudberget
Raudbergrgn.
VAIGATT-BOGEN
Poincartpn.
Legendretpn.
Halloytj.
Galoistpn.
Newtontpn. 1712m
Astronomtj.
Joguisrgn.
Oolerittfj.
Sillhøgda
Andromedatj.
Lava
Svarttpn.
Eljevepiggane
Enpiggen
Fulmarberget
OXFORDBREEN
GRUSDIEVBREEN
Macdonaldrgn.
Golitsynfj.
Bocklundtpn.
Svanbergfj.
Rogatsjevrgn.
Terriertj.
Chanslinfj.
Vivienberget
NEGRIBREEN
TUNABREEN
0 5 10kms.
LEGEND
Mixed snow & rock areas
Permo-Carboniferous C
U.Ma.U.Hecla Hoek UM
L.Middle Hecla Hoek
Lower Hecla Hoek L
Granite G
Thermal aureole
Mountain fj. fjellet
tpn. toppen
rgn. ryggen
Glacier bn. BREEN
Snow dome FONNA
Coastline

the result of incompetent folding which will be shown on independent evidence to apply to the overlying formations. A map showing this relationship appeared in a paper by Bayly (1957).

In conclusion, the more recent observations confirm our earlier views.

III. The Lower Veteranen Series

This series comprises the Veteranen Limestones and Veteranen Quartzites. It is now established in the Veteranen and Fakse areas and probably extends northwards to Dunérbreen. Recent field work shows that the thickness of the Veteranen Quartzites derived from the north Veteranen section (Harland and Wilson, 1956) was overestimated, and the reduced thickness was also found in Gullfaksebreen.

There are certain transitional beds separating the limestones from the quartzites which are usually found only as scree, but it is evidently these that are well exposed on either side of Dunérbreen. However, since correlation southwards is at present uncertain the boundary is left undefined.

Quartzites are always separated from the Planetfjella Series by calcareous beds, however thin, which are thought to be the same strata—the Veteranen Limestones—variously squeezed by incompetent folding. This squeezing is most pronounced in the areas of greatest regional metamorphism, i.e. north and south of the outcrop in Ny Friesland. Both Quartzites and Limestones tend to be paler in the more metamorphosed areas so that they have a superficial resemblance to analogous formations in the overlying series. The normal quartzites contain much iron oxide, and vary in colour from pinkish-brown, which is the most common, to grey-green, grey, brown, yellow, or more rarely, white, the latter being confined mainly to thin bands at the top and base of the formation. No attempt has been made to subdivide the quartzites on a basis of colour since in some outcrops (Langfjellet) a transition is visible along the bedding planes from one colour to another (pink to white, green or brown), and even short-range correlations based on colour have not proved effective. The quartzites are very uniform petrologically, and throughout are typically shallow water deposits. The Limestone Formation though not known in detail is much more variable, containing most of the rock types to be described in more detail under the Cavendishryggen Limestone Formation.

The outcrops of this series will be described in areas from north to south.

(*a*) *Heclahuken.*—The thick-bedded, dark-coloured coarse-grained

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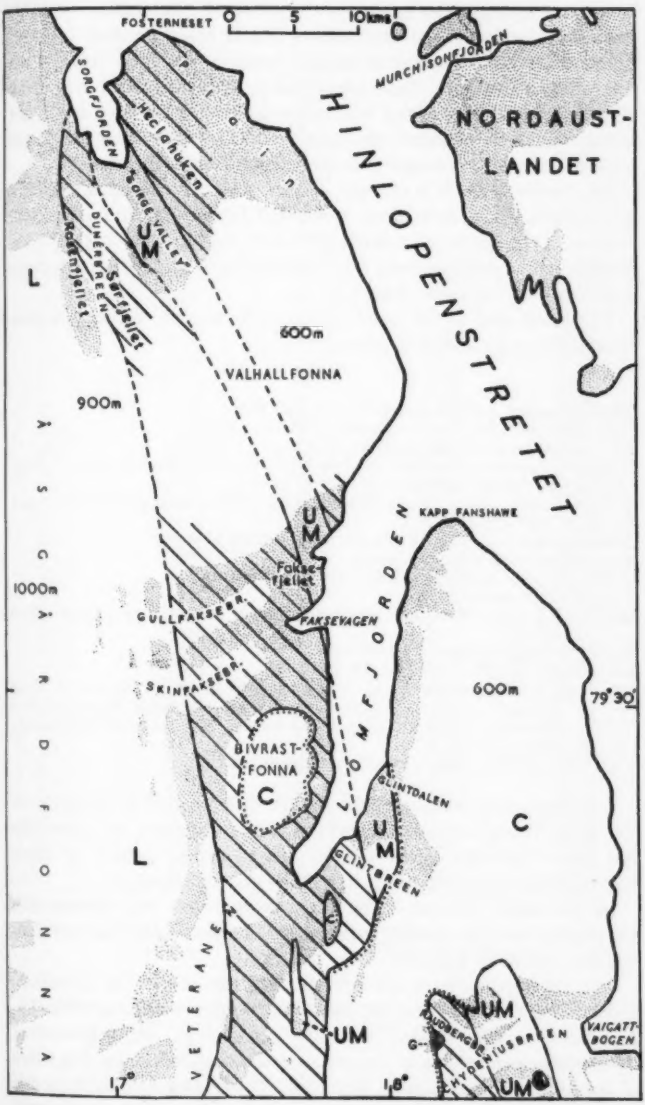
Text-fig. 2.—Sketch-map (1 : 500,000) of north-eastern Ny Friesland showing the distribution of the main rock groups and place-names referred to in the text. Legend as for Text-fig. 1.


FOSTERNESET
0 5 10kms
MURCHISONFJORDEN
NORDAUST-
LANDET
HINLOPENSTRETET
SORGFJORDEN
Heclahuken
Sorgevalley
UM
L
Rotenfjellet
Dunérbreen
Sørfjellet
600m
VALHALLFONNA
900m
KAPP FANSHAWE
UM
Fakse-
fjellet
1000m
GULLFAKSEBR.
FAKSEVAGEN
SKINFAKSEBR.
600m
79°30'
BIVRAST-
FONNA
C
GLINTDALEN
UM
GLINTBREEN
L
C
VETERANEN
UM
UM
Duebergbr.
G
HYDENIUSBREEN
UM
VAIGATT-
BOGEN
17°
18°

quartzites forming the eastern escarpment of Heclahuken probably belong to the Veteranen Quartzites. This is based on their lithology combined with their stratigraphical position near the core of the Heclahuken anticline. There also occur scattered outcrops of bedrock on Basisletta which has not been surveyed in the necessary detail, but which might be expected to include rocks of this series and even lower owing to the conspicuous southerly plunge of the anticline.

(*b*) *Dunérbreen.*—It is thought that the series is represented on both sides of the glacier in a much attenuated form owing to incompetent folding. The grade of metamorphism is higher than in the Fakse glaciers, and compares more with that found in mid-Veteranen where a similar effect has been inferred.

The lower part of the series, which includes part of the Veteranen Quartzites, is summarized below.

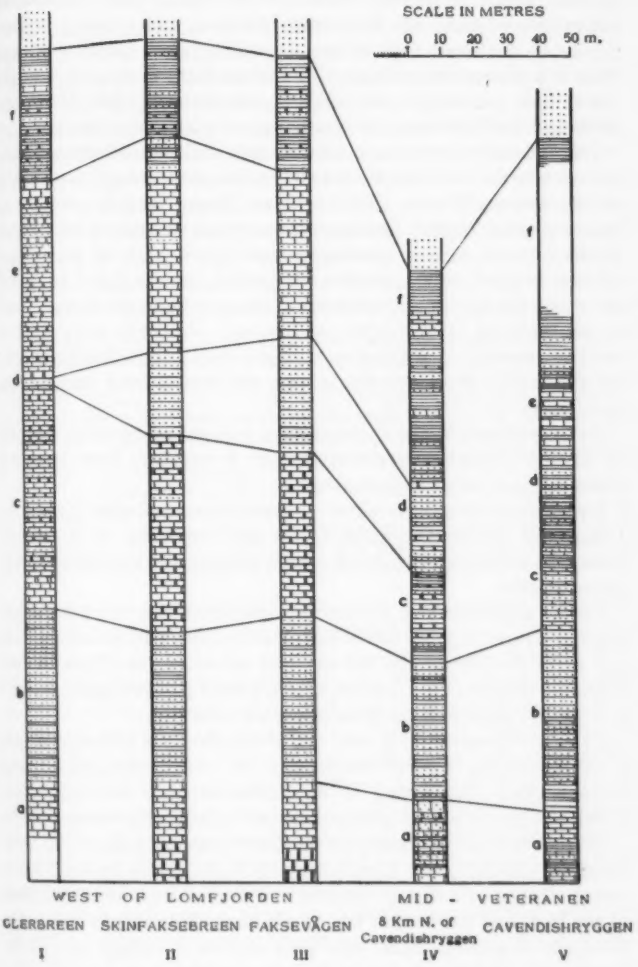
Top

Thickly bedded, pinkish quartzites (ca. 200 m.).
Pale green-grey, less coarse grained quartzites (30 m.).
Red and white tinted quartzite band (4 m.).
Laminated greywackes with a few thin bands of white quartzite (60 to 90 m.).
Grey-green, fine grained quartzite (15 to 18 m.).
White quartzite with a sharply defined, rusty-weathering upper surface (1 m.).
Reddish-black shales (8 m.).
Massive white quartzite, weathering pink-orange (3 m.).
Rusty-weathering quartzite (6 m.).
White quartzite weathering pale orange-brown (3 m.).
Purple-brown shales (1 m.).
Interbanded grey, black and brown-weathering dolomitic quartzites (20 to 60 m.).
Impure orange-weathering quartzites (45 m.).
Black shales, slightly schistose (15 m.).
Interbedded orange-brown and brown-weathering flaggy beds and black schistose shales. The orange beds are dolomitic quartzites, and there also occur black limestone bands. The rocks are all strongly sheared (15 m.).
Planetfjella Schists, with 3 m. of transitional beds.

The same section also appears on Sørfjellet and in both exposures the strata young towards the east, and it is supposed that the strike has been displaced across Dunérbreen by either a fault or sharp flexure similar to those which have been proved elsewhere.

(*c*) *The Fakse Glaciers.*—The whole series is very well exposed with the exception of the contact between the limestones and the quartzites which is obscured by scree.

The lower part of the Limestones, well exposed in the Skinfaksebreen nunatak, consists at the base of dark grey limestone siltstones, alternately thickly bedded and shaly, and with cream-weathering dolomitized equivalents of the same at frequent intervals. Examples of the abrupt lateral passage from dark limestone into pale dolomitic are well displayed. These beds contain abundant oolites with some



TEXT-FIG. 3.—Sections of the Cavendishryggen Limestone Formation from east central Ny Friesland. Detail within the subdivisions is diagrammatic. Thicknesses for I, II, and III calculated from pacing and photographs, and for IV and V from aneroid heights; scale 1 : 2,000, possible error 15 per cent.

pisolites which show only moderate distortion. The dolomitized equivalents of these are very rough, massive, and coarsely porous, similar to the basal beds of the Cavendishryggen Limestones, and there is a general resemblance of the whole formation to parts of the latter. Only in the upper part which is scree-covered in both Skinfaksebreen and Gullfaksebreen do quartzose rocks become important.

The Veteranen Quartzites are particularly well exposed in Gullfaksebreen where the vertically bedded and sombre-coloured quartzites form an impressive cliff face. The rocks are almost entirely medium or coarse grained, slightly ferruginous, quartzites weathering to various shades of pink, brown, green-grey, and yellow, with an uppermost horizon of pure white quartzite. A careful traverse failed to reveal any carbonate beds, conglomerates, or volcanic horizons, though there is one thick sill of epidiorite. Sedimentary structures such as false bedding, usually on a large scale, ripple-marks, and surface cracks are abundantly developed throughout, and surface trail marks occur at all levels.

As in Heclahuken, the Quartzites are brought up again to the east by folding, though only the upper part is proved. The rocks are much the same as those to the west.

(*d*) *Northern Veteranen.*—There is an excellent exposure of both the Limestones and the Quartzites on the north-west side of the glacier front, not yet surveyed in detail, which corresponds with those of the Fakse glaciers.

On the south-east side of Veteranen the Quartzites and Limestones outcrop extensively, somewhat disturbed by small-scale folding. At one point the Planetfjella Schists form an overturned flake on the mountain side, and the Limestones form a small jagged ridge analogous to a similar feature on the Skinfaksebreen nunatak.

(*e*) *Mid-Veteranen.*—The west wall of Galoistoppen is formed largely of the Quartzites, characteristically dark coloured, coarse grained, and without other rock types, as in Gullfaksebreen. Near the base of the section there is an unexpected intercalation of calcareous beds.

On the west side of Veteranen the Quartzites and Limestones both occur on Malloryfjellet, Langfjellet, and Kortfjellet. In the former two the Quartzite is strongly sheared and much thinner and paler than to the east, and well within the biotite zone of metamorphism. On Kortfjellet it appears darker and more variable as though part of the formation is faulted out, but no fault was located.

(*f*) *Terrierfjellet.*—The rocks here are in the biotite zone of metamorphism as well as being within the aureole of the nearby granite intrusion, and are plastically contorted on a small scale ; but the general pattern is similar to that on Malloryfjellet, the Limestones being inconspicuous and possibly partly faulted out in this case.

IV. The Middle Veteranen Series

This series comprises the Galoistoppen Beds, Cavendishryggen Limestones, and Cavendishryggen Quartzites. It differs from the Upper and Lower Veteranen Series in being much more variable in its detailed stratigraphy and containing a wider variety of rock types. The best exposures occur in the Fakse area and in Veteranen, and no measurements have been made elsewhere. The only previous description of the petrology is by Fairbairn, who collected from the east side of Southern Veteranen, most probably from the lowest part of the series, and since his description of a typical specimen of the " slates " (termed greywackes by the author) is found from our own section to apply in general to nearly all the dark rocks of the Veteranen Series except the limestones, an extract is quoted here (1933, pp. 451–2):—

> " A hard, compact, dark grey rock, with poorly developed slaty cleavage. The original bedding is clearly visible in the form of a number of dark bands, which average about twenty to the inch, and are much puckered and contorted. These beds are proved by heating to consist of carbonaceous matter. In thin section some bands are seen to be composed of finely divided opaque matter which cannot be resolved into individual grains; many show overfolding and overthrusting on a small scale, and the rock has evidently developed a strain-slip cleavage.
>
> Other bands consist of isolated grains, and many of this latter type contain a considerable proportion of chlorite. The intervening areas are composed of finely divided quartz and sericite, with a number of subangular clastic quartz grains. They may occur as isolated beds, but more commonly as definite bands, or as lenticles and aggregates enclosed by the dark bands."

Our sections show that this description applies widely if account is taken of the known variations of metamorphic grade ; thus in some western areas the rocks are strongly cleaved with the production of biotite (and even garnet appears in Waynefletefjellet, though this might be the result of superimposed thermal metamorphism), while in eastern areas both puckering and contortion may be absent. Detrital feldspar (of very variable composition) is present in a high proportion of the slides, and in a few cases comprises 30 per cent of the rock. Chlorite is always present, and in the less metamorphosed greywackes some of it appears to be detrital in origin. Interstitial carbonate is also common even in many of the very hard rocks, and there is every gradation from carbonate-bearing greywackes to pure limestones and dolomites.

Two thin lava bands occur at different horizons and localities. These are the only extrusives known from Ny Friesland in the Middle and Upper Hecla Hoek.

The rocks are discussed in areas from north to south:—

(*a*) *Heclahuken.*—Since outcrops are discontinuous and the rocks disturbed a good section is not seen, but the author repeated Kulling's traverse confirming his observations and recognizing from west to east the Upper and Lower Cavendishryggen Quartzites, the Caven-

dishryggen Limestones, and the Galoistoppen Beds which occupy a long low outcrop just west of the inferred position of the Heclahuken anticline. Thicknesses estimated from dips and widths of outcrop seem excessive (*ca.* 7,000 m.), and there may be strike faulting.

(*b*) *Dunérbreen.*—Below the northern peak of Sørfjellet there occur some low-lying outcrops containing calcareous horizons with quartzites and greywackes closely similar to the association found in the Cavendishryggen Limestones further south, and there can be little doubt of this correlation. This strengthens the case for placing the main Sørfjellet rocks within the Lower rather than the Upper Veteranen Series.

(*c*) *The Fakse Area* (see Plate VII, fig. 2).—Since the stratigraphy is known in more detail here than elsewhere, the beds (originally defined further south) are described separately in the following order :—

Lower Galoistoppen Beds.
Upper Galoistoppen Beds.
Cavendishryggen Limestones.
Cavendishryggen Quartzites.

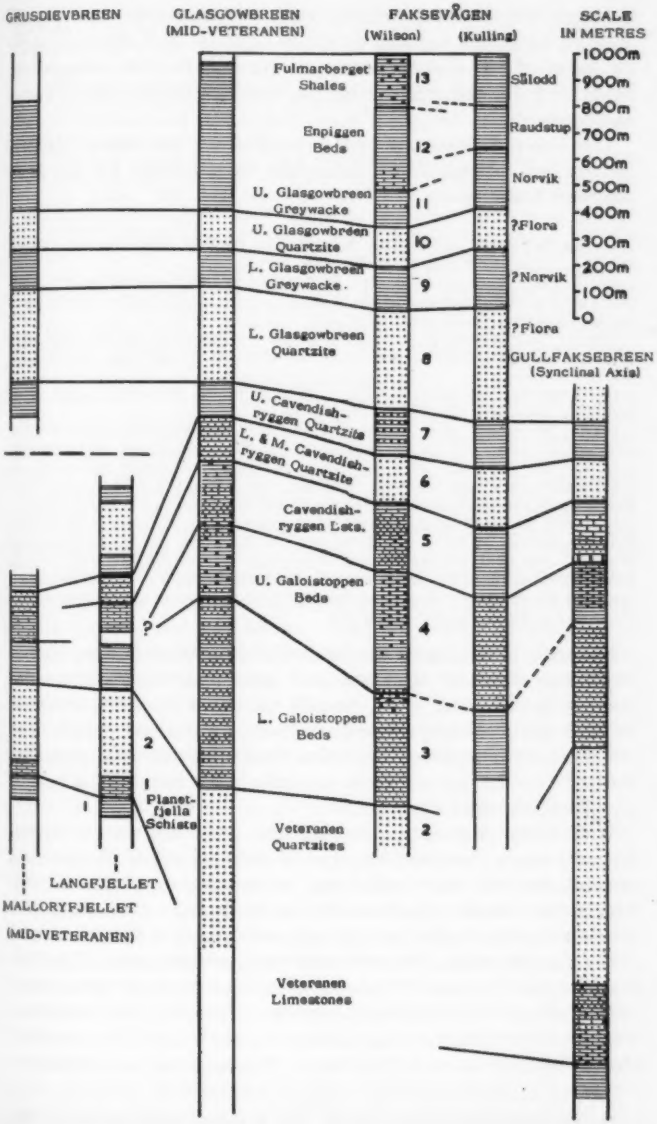
The *Lower Galoistoppen Beds* are particularly well exposed in Gullfaksebreen and Skinfaksebreen where their lithology is remarkably uniform except for the upper 60 m. which are finely laminated and dolomitic. The main rock type is a thickly bedded, dark green-grey medium-grained quartzose greywacke or impure quartzite with subordinate shaly intercalations of the same material. Thin sections show that it consists of rounded quartz grains, both well and poorly sorted (often accompanied by feldspar) and loosely packed in a dirty matrix of clay-iron oxide with carbonate, prochlorite, and white mica. Some bands are brecciated by white quartz veins. The upper 60 m. consist of interlaminated green-grey quartzite, sometimes dolomitic, and black shales. No volcanic horizons were found.

Towards the east where the rocks are brought to the surface twice more by folding, the lithology changes slightly, the rocks becoming less uniform and containing some pale grey quartzite and " black-coated flags ". The latter are thinly bedded pale grey-green quartzites with film-like partings of black shale which give the scree a very dark appearance. This rock type is particularly characteristic at higher horizons. The uppermost beds are highly dolomitic, laminated, and shaly.

Two bands of altered lava about 1 metre thick were discovered on

---

TEXT-FIG. 4.—Correlation table of the main sections of the Lower Middle Hecla Hoek rocks from central and southern Ny Friesland. Scale 1 : 25,000.


GRUSDIEVBREEN
GLASGOWBREEN
(MID-VETERANEN)
FAKSEVÅGEN
(Wilson)
(Kulling)
SCALE
IN METRES
1000m
900m
800m
700m
600m
500m
400m
300m
200m
100m
0
Fulmarberget
Shales
Enpiggen
Beds
U. Glasgowbreen
Greywacke
U. Glasgowbreen
Quartzite
L. Glasgowbreen
Greywacke
L. Glasgowbreen
Quartzite
U. Cavendish-
ryggen Quartzite
L. & M. Cavendish-
ryggen Quartzite
Cavendish-
ryggen Lets.
U. Galoistoppen
Beds
L. Galoistoppen
Beds
Veteranen
Quartzites
13
12
11
10
9
8
7
6
5
4
3
2
Sälodd
Raudstup
Norvik
?Flora
?Norvik
?Flora
GULLFAKSEBREEN
(Synclinal Axis)
?
2
1
Planet-
fjella
Schists
LANGFJELLET
MALLORYFJELLET
(MID-VETERANEN)
Veteranen
Limestones

the south side of Skinfaksebreen snout. Unfortunately the original minerals have been replaced by calcite, chlorite, and chert and only the shapes of the original phenocrysts are clearly visible. One of the bands has a pillowed upper surface, and both have chilled margins above and beneath.

The *Upper Galoistoppen Beds* outcrop along the Fakse Glaciers, but are best exposed in the Faksevågen section (Plate VII, fig. 2) as described below:—

BASE

(i) A conspicuous and sharply defined basal band of white quartzite which serves as a marker horizon for the area. (9 m.)

(ii) Brightly coloured laminated dark red-brown and pale green-grey non-calcareous paper shales occurring in layers about 10 m. thick in which each colour predominates in turn. (110 m.)

(iii) As (ii) but containing layers of cream-weathering dolomitic flags, and one clearly defined band of coarse-grained ferruginous quartzite, about 1 m. thick. (30 m.)

(iv) Scree-covered ground with a mixture of all the above rock types including some pale quartzites. (140 m.)

(v) Purple-brown, pale green-grey, and cream-weathering beds in close alternation. These are thickly bedded though finely laminated, and although very soft are relatively resistant to weathering. The cream bands are of false-bedded dolomite siltstone, and the purple and green layers are very fine grained, the latter containing much dolomite. These layers are commonly interrupted by seams and lenticles of coarse-grained, strongly false-bedded pinkish quartzite up to ½ m. in thickness, and the whole gives the appearance of mixed chemical and mechanical deposition in very shallow water. The dolomites in particular contain abundant desiccation cracks and trail marks. Pure calcite seems to be absent from this division, and the purple layers disappear towards the top. (180 m.)

Elsewhere in this region the topmost beds consist of cream-brown-weathering dolomitic flags and pale green-grey beds. The latter occur as thin shales of white, coarsely crystalline limestone separated by films of a green-grey micaceous substance. This unusual lithology has not been observed at any other level. This division passes up abruptly into the coarse massive dolomite bands marking the base of the Cavendishryggen Limestones.

West of the Faksedalen anticline the rocks are similar though generally more quartzose, but usually only the upper divisions are exposed, the soft lower beds being marked out by gullies. A few thin layers of black limestone-siltstone associated with porcellanous brown and green-weathering dolomites were found in Skinfaksebreen.

The *Cavendishryggen Limestones* are well exposed in several localities and Text-fig. 3 shows the supposed correlation between the sections, most of which were only roughly measured. However, it is evident that there is a definite sequence applicable to the whole area with no marked changes of facies or overall thickness. The sequence is as follows:—

BASE

(i) Limestones and dolomites 30 m. This is a pure carbonate division the

base of which usually consists of a conspicuous pale-weathering massive dolomite. This rock is rough-weathering and coarsely porous, and north of Skinfaksebreen terminal moraine it can be seen to pass locally along the bedding planes into grey-black oolitic limestones, which rock type comprises the remainder of the division. The large pores in the dolomite are probably the result of differential removal of ooliths during or after dolomitization, and this development is remarkably like that found at the base of the Veteranen Limestone Formation.

(ii) Quartzose beds 50 m. These are almost entirely made up of pale green-grey impure quartzites with horizons of "black-coated" quartzite flags and shales. The rocks become more thickly bedded towards the top.

(iii) Calcareous beds 50 to 70 m. This is a mixed division of brown-weathering dolomitic flags alternating with and sometimes passing laterally into grey-black oolitic limestone, and in the upper part with bands of impure quartzite, often "black-coated". These quartzites are usually sharply defined, often lenticular, and both limestone and quartzite are strongly false bedded. In Rimfaksebreen the carbonate rocks are also partly silicified.

(iv) Quartzose beds 4 to 35 m. This is a distinctly quartzose division containing little or no carbonate, and very variable in thickness if the correlations are correct.

(v) Calcareous beds 50 to 70 m. similar to (iii).

(vi) Shales 35 m. This differs from all the above in containing much purple-brown and green-grey shale as well as cream-weathering dolomitic shale. There is much coloured quartzite towards the top, and one thin horizon of grey-black limestone. In Rimfaksebreen the purple layers are dolomites containing oolites and flake conglomerates, and the green layers are of pale coarse-grained sandstone with green-coated surfaces. Towards the top the carbonate content fails completely and the rocks become purple and green quartzose shales and flags which grade quickly into the overlying Quartzite Formation.

The *Cavendishryggen Quartzites* have a development similar to that in Veteranen except that the rocks have a stronger resemblance to those of the Upper Veteranen Series. Thus only two divisions can be recognized, the lower of which is almost identical with the Lower Glasgowbreen Quartzite, and the upper one to the Glasgowbreen Greywacke. Since the lower division has a thickness approaching that of the combined lower and middle divisions in Veteranen, it is supposed that the green-grey quartzites of the latter have become thickly bedded pinkish quartzites here.

(*d*) *Glintbreen.*—Bordering the lower part of Glintbreen there is an extensive outcrop of the Cavendishryggen Quartzites disturbed by faulting. As in Veteranen (see under) they fall into three divisions, the lowest of which differs in appearance from the pinkish-white Glasgowbreen Quartzite in being brown in colour, strongly banded, and with layers of dark shale. The upper division is seen to be more variable in the lower part than has been noted elsewhere, including pale brown weathering dolomitic beds, and green-grey and blue-black quartzose shales and flags. Of special interest is the discovery of a 3 m. band of massive dark grey limestone containing abundant flat-lying *Collenia* colonies (Plate VIII, fig. 3). This is the only example of *Collenia* known from the Lower Middle Hecla Hoek. The band is repeated three times along the glacier wall, but this is thought to be due to faulting. The

remainder of the formation is mainly of " black-coated " flags as elsewhere.

Further south the Galoistoppen Beds are exposed, and the white quartzite band and purple shales marking the base of the Upper Beds in the Fakse area are again observed here.

(*e*) *Northern Veteranen.*—The high north-west wall of the glacier which gives an almost continuous exposure of the series has not been surveyed, but along the south-east margin there are some water-worn exposures very similar to those of Skinfaksebreen gorge both in lithology and physiographical setting.

(*f*) *Mid-Veteranen.*—The east wall sections (Plate VII, fig. 3), though ideally disposed, are disturbed by small-scale overfolding and strike faulting so that the estimated thicknesses are rather uncertain. West of the glacier this uncertainty is much greater since the rocks are in the biotite zone and are greatly squeezed with the destruction of the finer characteristics; however, a comparison of lithologies leaves little doubt that the rocks of Langfjellet and Malloryfjellet correspond with those of Glasgowbreen. This is confirmed by a comparison of formational thicknesses which are all reduced in approximately the same proportion.

The Lower Galoistoppen Beds are better exposed on the eastern wall of Veteranen north of Glasgowbreen than on Galoistoppen where they are rather inaccessible. The Formation consists of uniform grey-black and dark green-grey greywacke flags and shales with subordinate impure flaggy quartzites. Surfaces frequently weather to various shades of rust and yellow-orange. The grain size is medium to fine with a fine lamination of dark and less dark layers, often with fine false bedding.

The Upper Galoistoppen Beds are not so well developed as in the Fakse area owing to an increased quartzitic content at the expense of carbonate; however, the same striking rock types and associations occur. The base is taken as the lower of two thin bands of white quartzite which it is thought are roughly equivalent to the single band in Faksevågen, though the purple shales of that area are not seen here. The Upper Galoistoppen Beds have not been seen west of Veteranen, but this may be due to poor exposure.

The Cavendishryggen Limestones (Plate VII, fig. 3) are also less well developed than to the north, much of the carbonate being replaced by quartz, as is strongly suggested by the sections in Text-fig. 4. The sixfold subdivision of the Fakse area is just recognizable. Oolites are conspicuous only at the base of the sections, and the higher calcareous divisions are poorly developed though frequently dolomitic.

The Cavendishryggen Quartzites are excellently exposed north of Glasgowbreen and fall into three well-defined divisions, the lowest

of which is of alternating massive bands of variously tinted pure quartzite with thinner partings of rusty-weathering quartzose shales and flags, and a very few thin layers of dark dolomitic limestone. The massive quartzite contains many surfaces with trail marks, and the whole is characterized by strong false bedding. The middle division is of uniformly medium bedded, pale green-grey medium to fine grained quartzites without intercalations of other rock types, capped by a 3 m. band of pure white quartzite ; the rocks appear dark from a distance owing to a black lichen which grows on these greenish quartzites. The upper division consists largely of " black-coated " flags and shales of the same greenish quartzite as in the middle division : greywackes and calcareous beds are subordinate. Four metres above the base of the division there occurs a ½ m. band of vertically jointed lava similar to that of Skinfaksebreen. Its minerals are similarly replaced by calcite, chlorite, and chert with the relicts of phenocrysts clearly visible. The formation is well exposed on Langfjellet and Malloryfjellet where all three divisions are seen in a much attenuated form.

(*g*) *Lower Chydeniusbreen.*—The lowest beds exposed in the Raudbergryggen anticline belong to the Cavendishryggen Quartzites, and in spite of thermal metamorphism by the nearby granite the succession can be seen to be so similar to that of Veteranen that no marked change of facies can be inferred from west to east.

(*h*) *Southern Ny Friesland.*—The series doubtless continues southwards through southern Chydeniusfjella where dark limestones have been found, but occurrences are too scattered for any useful correlations to be made.

V. The Upper Veteranen Series

In spite of the abundance of outcrops none is complete, those of Grusdievbreen, Veteranen (Plate VII, fig. 3), Glasgowbreen, and Faksevågen (Plate VII, fig. 1) being the best. Recent field work has shown that a four-fold division can be applied everywhere, for which reason the original scheme (1956) is modified thus:—

Harland and Wilson, 1956.	*This Paper* (Text-fig. 4).
Glasgowbreen Greywackes .	Upper Glasgowbreen Greywackes Upper Glasgowbreen Quartzite Lower Glasgowbreen Greywackes
Glasgowbreen Quartzite .	Lower Glasgowbreen Quartzite

The Lower Quartzite is everywhere a very prominent formation with a sharp lower boundary, thus providing an excellent marker horizon at the base of the series. The upper boundary of the series as defined in Grusdievbreen (Plate VIII, fig. 1) can also be applied in central Ny Friesland, and agrees with that separating the Norvik-Raudstup Series of Nordaustlandet; and as explained later the

discrepancy between the positions in Faksevågen is thought to be due to misinterpretation.

The Lower Quartzite is similar everywhere and forms prominent features as for instance on Heclahuken, Langfjellet, and Chydeniusfjella. The normal rock is a coarse grained, thickly bedded pale pinkish false-bedded quartzite without other rock types. The colour varies a little from place to place, thus in south Ny Friesland and Veteranen the lower part is the more ferruginous, the reverse being true in Faksevågen. In most areas there is a thin band of white quartzite marking the base, and in the south the topmost beds are also white. Where the metamorphism is more severe as on Langfjellet the thickness is much reduced and the colour much paler and more varied with transitions of colour along bedding planes. Both upper and lower boundaries are very sharp.

The Lower Greywackes in sharp contrast with the above are clean greenish-black, very fine grained greywackes, finely laminated in dark and less dark layers with carbonaceous films, and the same lithology persists throughout with the exception of occasional clearly defined ½ m. bands of coarse grained white quartzite. Massive beds, flags, and shales intermingle with variable thickness. Fairbairn's petrological account quoted above also describes this rock, and calcite is rare or absent. The formation passes up by transition into the Upper Quartzites which in Grusdievbreen greatly resemble the Lower, but which in central Ny Friesland are more variable and bear more resemblance to the Lower Cavendishryggen Quartzites. The formation is not conspicuous in north Ny Friesland. The Upper Quartzite is well exposed in south Glintbreen, where the base is of interbedded deep purple, green-brown, and yellowish-white shaly quartzites which become more thickly bedded upwards and of brownish colour, with a 12 m. intercalation of black shales near the top, which is here as elsewhere very sharp. This development is very similar to that in Faksevågen.

The Upper Greywackes are in every way similar to the Lower in Grusdievbreen and south Glintbreen, but in Faksevågen this formation is scree-covered, and the material of the scree resembles Enpiggen Beds more than normal greywacke, for which reason this section is still in some doubt. The formation has received little study in other areas.

Another outcrop is that of Raudbergryggen in lower Chydeniusbreen, first visited by Odell (1927) and described as " red shales of uncertain horizon ". During 1956 I became convinced that these are the normal quartzites and greywackes of the Middle and Upper Veteranen Series greatly altered by thermal metamorphism with the production of heavily spotted hornfels: these have been much impregnated with

iron oxide which has converted all the rocks to the deep rust colour. The thicknesses are similar to those in the west.

Finally the Sherborne/Cambridge Expedition, 1954, discovered 300 m. of pink and white quartzites in a nunatak at the head of Tunabreen which probably belong to the Lower Glasgowbreen Quartzite.

In conclusion the series is a simple one composed of only two lithological types—coarse grained quartzite and fine grained greywacke, which occur in broad alternation. The stratigraphy is remarkably uniform throughout central and southern Ny Friesland, but the upper formations may differ somewhat in the north.

VI. The Oxfordbreen Series

This series comprises the Enpiggen Beds and Fulmarberget Shales. I visited several additional exposures of the series in 1957, including that of Faksevågen (previously seen by Kulling), and found the latter to have a greater general resemblance to the Sälodd and Raudstup Series of Murchisonfjorden than Kulling supposed. Other sections further south indicate that this similarity extends uniformly into southern Ny Friesland. This differs from the views expressed by Fleming and Edmonds (1941), and Harland and Wilson (1956) which were based on incomplete evidence. The lithology appears to be similarly developed throughout the area, and sample observations are listed below.

On Japetusryggen the lower boundary is sharply defined by the appearance of less dark, variously coloured and laminated quartzose beds above the uniform grey-black greywackes of the Glasgowbreen Series. This line is thought to correspond with the base of the Raudstup Series in Nordaustlandet, though as explained later the Faksevagen section is unsatisfactory in demonstrating this.

The Enpiggen Beds and Fulmarberget Shales are of distinct lithology but a boundary is not easy to fix, the most convenient line being that at which bright red paper shales make their first appearance. Although this may not coincide with the base of the Sälodd Series in Murchisonfjorden it is the nearest available marker horizon and can be applied effectively to most of Ny Friesland including Faksevågen.

The top of the series is everywhere clearly defined by the abrupt appearance of the dolomites and limestones of the Grusdievbreen Series: the lower beds of the latter are often dolomitic and pale-weathering, making the boundary inconspicuous from a distance (Plate VIII, fig. 1).

The rocks are described in areas from north to south:—

(*a*) *Faksevågen.*—The following section includes the Upper Glasgow-

breen Greywackes (Division 1) since the position of the lower boundary is uncertain.

Top

7. Mainly pale green-grey, highly dolomitic shales with some pure dolomite-siltstone. Near the top there occur a few conspicuous thin conglomeratic layers with flat pebbles of dark grey limestone-siltstone up to 20 cm. across set in a matrix of coarse-grained white quartzite. (140 m.)
6. Interbedded pale green-grey and bright red-brown, slightly dolomitic shales with layers of pale weathering dolomitic quartzite. (70 m.)
5. Mainly dark green-grey shales and brown-weathering, pale quartzose flags, all virtually non-calcareous, passing down into:—
4. Blue-black, fine grained greywacke shales and flags, almost non-calcareous. (4 and 5; 210 m.)
3. Dark quartzose flags interbedded with grey-black limestones, sometimes dolomitic. (90 m.)
2. Grey-black bedded limestone-siltstones. (10 m.)
1. Mixed dark beds including grey-black, brown, dark purple-brown, and grey-green quartzose shales and flags, some slightly dolomitic and some " black-coated ", with a few ½ m. bands of pure white quartzite; however, the whole is much scree-covered and the lower part may contain more of the grey-black greywacke type as indicated by Kulling (1934). (140 m.)

Divisions 7 and 6 make up the Fulmarberget Shales, and divisions 5, 4, 3, and 2 the Enpiggen Beds.

(*b*) *Lower Chydeniusbreen.*—There is a fairly complete exposure in Raudbergbreen, but the rocks are strongly hornfelsed near the granite. A partial exposure on the south wall is unvisited.

(*c*) *Polarisbreen* (Plate VIII, fig. 2).—There is an excellent exposure of the Fulmarberget Shales which are thicker than usual (350 m.). The rocks seem to be more variegated with closely interbanded red-brown, yellow, and pale green-grey weathering shales and flags, reminiscent of the strata at the top of the Upper Galoistoppen Beds. There is much fine shale in the lower part, and a high dolomite content only appears towards the top. The upper part of the Enpiggen Beds contains red-brown, green, grey, blue-black, and pale brown-weathering quartzose flags and shales, some of them " black-coated " and some dolomitic. Dark reddish quartzose shales are common towards the top, but differ in colour from the more strongly coloured red shales marking the base of the Fulmarberget Shales.

(*d*) *Oxfordbreen and Grusdievbreen.*—The base of the series is defined on Japetusryggen, but exposures are small and scattered and no detailed stratigraphy is available. All evidence indicates that the sequence is the same as that further north.

The Enpiggen Beds of the type locality are noteworthy for the close alternation of very fine shales, flags, and thickly bedded layers all of similar lithology but of differing and rather dirty shades. Individual bands, some only a few millimetres thick, can be traced

across the cliff face without apparent change of thickness. Sedimentary structures such as false bedding and ripple marks are almost absent though some of the paler bands are quite coarse grained. A few bands are slightly dolomitic.

In Oxfordbreen the upper part of the formation contains very subordinate layers of conglomerate, with fragments of limestone and dolomite in a matrix of impure quartzite. This curious lithology, rather similar to that in the Fulmarberget Shales of Faksevågen, has not been found in any other series in the Hecla Hoek. It appears to result from the pene-contemporaneous desiccation of thin carbonate bands, and there may be a connection here with the limestone horizon at the base of the formation further north.

The Fulmarberget Shales of the type locality consist, as in Faksevågen, of a thick group of mainly grey-green dolomitic shales overlying a thinner and less dolomitic group in which red-brown shales are interbedded, the total thickness being about 220 m.

(*e*) *Transparentbreen.*—The whole series may be exposed on Rogatsjevryggen but has not been examined in detail. It is disturbed by a strike fault which may account for the small apparent thickness (*ca.* 120 m.) of the Fulmarberget Shales.

VII. Comparison with Nordaustlandet

De Geer and Kulling who visited both Nordaustlandet and Ny Friesland stressed the similarity of the Hecla Hoek in the two areas, and Kulling was convinced that the Murchisonfjorden stratigraphy applied to Lomfjorden. Since the Faksevågen section is the only one from which a satisfactory sequence was obtained it is discussed in some detail.

Comparing the section by formations, the Fulmarberget Shales are broadly equivalent to the Sälodd Series, but since the lower boundary of the latter is transitional in Murchisonfjorden and was not located by Kulling in Faksevågen, I have used the division previously chosen in the south which applies also to this outcrop. I find the principal rock type to be more dolomitic than Kulling described it, thus increasing the similarity with Murchisonfjorden. The Enpiggen Beds, especially towards the top, also contain a high proportion of rocks which precisely fit the description of the Raudstup Series, but they are by no means all shales, and contain besides some grey-black greywacke and dark limestone. The lower boundary is obscured by scree, but does not coincide with Kulling's position for the base of the Norvik Series which may be in error since he states that the basal beds of the Raudstup Series differ from those in Murchisonfjorden. The minimum thickness of the Norvik Series in Nordaustlandet (350 m.)

is greater than anything in the Faksevågen section, and since no thin quartzite division (Kulling's division " E ", or the Upper Glasgowbreen Quartzite) is found in Nordaustlandet, I suggest that this loses its identity to the north-east and that the Norvik includes also the Lower Glasgowbreen Greywackes. The lower Glasgowbreen Quartzite would then correspond precisely with the Flora Quartzite. Further down than this no useful comparison can be made, but in view of the cyclic sedimentation demonstrated in Table 1 it is possible that some Nordaustlandet rocks may have been misidentified. Thus in northern Ny Friesland, for example, Kulling (in his classic reconnaissance) mistook the Upper Galoistoppen Beds for the Sälodd Shales (Fulmarberget Shales) with the result that a false impression of the structure was gained.

Sandford (1956) demonstrated with several sections from central and northern Nordaustlandet that the stratigraphy varies little across this area, but although agreeing well with each other all the sections differ in important respects from those of Ny Friesland, and I should hesitate to make any correlation. If Sandford's interpretation is correct there is a greater difference of facies between his sections of the Flora Series and those of Murchisonfjorden than there is between the latter and those of Ny Friesland: furthermore there is a general thickening of the Lower Murchison Bay Formation from Ny Friesland to Murchisonfjorden, and the greater thicknesses are maintained towards the north-east. This is hard to reconcile with the reduction of at least 11,000 m. of underlying sediments in Ny Friesland to 750 m. Kap Hansteen Formation in Nordaustlandet. It appears to the author that the presence of only such relatively thin sediments below the Flora Series, if confirmed, is a rather surprising result.

VIII. Discussion

Viewed as a whole the succession is one of frequent and irregular repetition of a limited number of rock types, the most common of which are pale quartzite and dark greywacke which are usually separated by sharp boundaries. Sedimentary repetitions are present on every scale from the smallest to the largest and are tabulated as follows:—

(i) Microscopic lamination as little as one grain thick in the fine grained greywackes, often produced by carbonaceous films.
(ii) Fine lamination of purple and green paper shales, on which larger alternations are superimposed.
(iii) Interbanding of dolomite-siltstone, red and green shales, and sharply defined quartzite lenses.
(iv) Interbanding of dark limestones (oolitic), impure quartzites, and thin shales.

(v) The " black-coated " flags: impure quartzite flags separated by fine black shale films.
(vi) The interbanding of varied impure quartzose beds as in the Enpiggen Beds.
(vii) The larger scale alternation of quartzite and greywacke composing much of the succession.
(viii) Repetition of the whole sedimentary cycle.

Of these the last is of most interest, for the facies cycle in the lower half of the succession is repeated even in detail in the upper half, as is seen on examining Table 1.

It will have become clear from the foregoing that this repetition cannot be tectonic but comprises a continuous sequence. The general cycle: quartzite—greywacke—green and red shales—dolomitic beds—dolomite—limestone is what might be predicted on the simplest assumptions in the case of a relatively rapid though somewhat intermittent uplift of the source area (unknown) followed by a gradual reduction to sea level, accompanied by a more or less continuous subsidence of the area of deposition. However, superimposed on this are cyclical changes in colour of the sediments as a whole, and a cycle of carbonate deposition. The abundance of oolites, the absence of any sedimentary features suggesting secondary derivation, and the absence of any known source rocks make it very unlikely that the carbonate rocks are detrital, and they were probably precipitated in the absence of clastic material. If so the existence of a distinct facies cycle within the carbonate rocks themselves could not be directly related to crustal movements in the source area, but rather to climatic and oceanographical factors in the area of deposition. The remarkable repetition of the colour, carbonate, and clastic facies cycles in the same manner on two separate occasions suggests a close relationship between crustal elevations in the source area on the one hand, and climatic and oceanographic changes on the other. If this were the case similar cycles in other successions would be expected.

It will be recalled that the rocks described above fall within a much thicker succession the lower part of which is largely non-calcareous and the upper part poor in quartzitic sediments. These rocks then reflect a distinctive phase in the development of the Ny Friesland geosyncline.

Finally, I wish to express my gratitude to Mr. W. B. Harland who originated this work and who has helped greatly throughout; to all the members of the expeditions referred to, especially Mr. M. B. Bayly, and to Mrs. K. Herod for drawing the text-figures. I am also indebted to Professor W. B. R. King and Professor O. M. B. Bulman for research facilities in the Sedgwick Museum.

TABLE 1.—THE LOWER MIDDLE HECLA HOEK ROCKS ARRANGED IN LITHOLOGICAL GROUPS SO AS TO ILLUSTRATE THE REPETITION OF A SEDIMENTARY CYCLE

GRUSDIEVBREEN SERIES.	Lower Grusdievbreen Limestones.	Dark limestones. Dolomitic limestones with a dolomite base.	600	260	Oolitic limestones, grey quartzites, and black shales with a base of massive dolomite.	Cavendishryggen Limestones.	MIDDLE VETERANEN SERIES.
OXFORDBREEN SERIES.	Fulmarberget Shales.	Pale green, red and cream-weathering dolomitic beds.	50	200	Pale green, red and cream-weathering dolomitic beds with pure quartzite lenses.	Upper Galoistoppen Beds.	
		Red and green quartzose paper shales.	160	250	Red and green quartzose paper shales.		
	Enpiggen Beds.	Dark green-grey dolomitic shales with greywackes and grey quartzites.	450	60	Dark grey-green dolomitic shales.	Lower Galoistoppen Beds.	
UPPER VETERANEN SERIES.	U. Glasgowbreen G.	Alternating greywackes and mainly pink quartzites.	1,100	400	Grey quartzites, black coated quartzites, and greywackes.		
	U. Glasgowbreen Q.						
	L. Glasgowbreen G.						
	L. Glasgowbreen Q.						
	U. Cavendishryggen Q.			900	Mainly pink quartzites.	Veteranen Quartzites.	LOWER VETERANEN SERIES.
	M. and L. Cavendish-ryggen Q.						
		Mixed coloured quartzitic and shaly beds.	40	150	Mixed coloured quartzitic and shaly beds.	Veteranen Limestones.	
MIDDLE VETERANEN SERIES.	Cavendishryggen Limestones.	Oolitic limestones, grey quartzites, and black shales with a base of massive dolomite.	210	200	Oolitic limestones, impure quartzites, and black shales with a base of massive dolomite in some localities.		
				2,500 metres	Black Schists.	Planetfjella Schists.	PLANETFJELLA SERIES.

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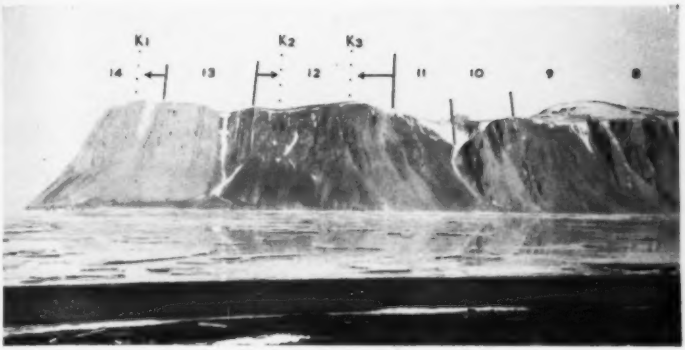

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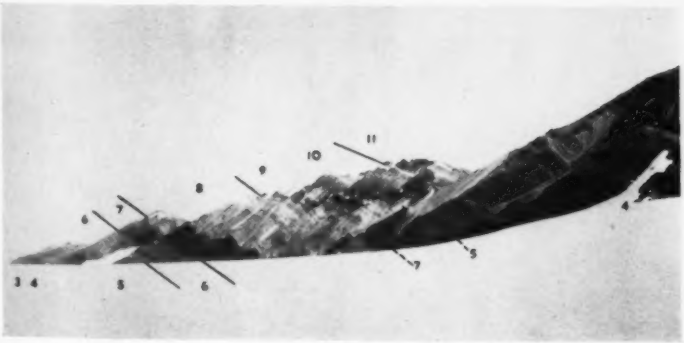

LOWER MIDDLE HECLA HOEK ROCKS IN NY FRIESLAND.

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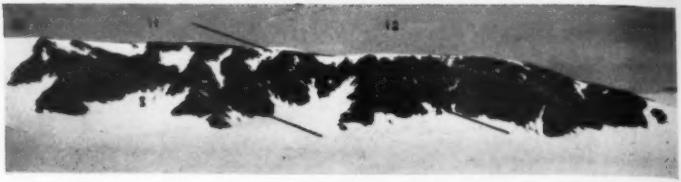

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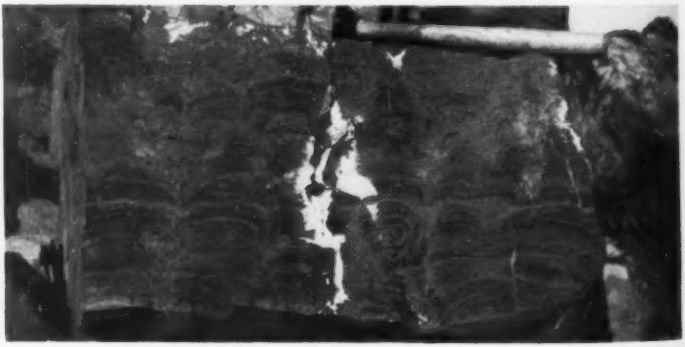

LOWER MIDDLE HECLA HOEK ROCKS IN NY FRIESLAND.

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EXPLANATION OF PLATES

PLATE VII

FIGS. 1 AND 2.—The eastern and western ends of the Faksevågen cliff section seen from along the strike looking southwards. K_1, K_2, K_3 indicate the approximate boundary lines suggested by Kulling (1934).

FIG. 3.—The mid-Veteranen section looking north from near the mouth of Glasgowbreen.

Key to numbers on photographs:—

2 the Veteranen Quartzites.
3 and 4 the Lower and Upper Galoistoppen Beds.
5 the Cavendishryggen Limestones.
6 the Lower and Middle Cavendishryggen Quartzites.
7 the Upper Cavendishryggen Quartzites.
8 and 10 the Lower and Upper Glasgowbreen Quartzites.
9 and 11 the Lower and Upper Glasgowbreen Greywackes.
12 the Enpiggen Beds.
13 the Fulmarberget Shales.
14 the Lower Grusdievbreen Limestones.

PLATE VIII

FIG. 1.—The eastern end of Japetusryggen, Grusdievbreen, showing the boundary between the Upper Veteranen and Oxfordbreen Series. Key as for Plate I.

FIG. 2.—The upper part of the Fulmarberget Shales of Polarisbreen, with the lower, more shaly part in the background. The height of the cliff is approximately 150 m.

FIG. 3.—*Collenia* from a 3 m. band of dark limestone in the Upper Cavendishryggen Quartzites of Glintbreen, Lomfjorden.

New Occurrences of Fish Remains in the Silurian of the Welsh Borderland

By H. C. Squirrell

Abstract

The important records of fish remains in the Ludlow Series and Ludlow Bone Bed of the Welsh Borderland are summarized. New occurrences of thelodont and acanthodian denticles in the Llandovery, Wenlock, and Ludlow Series of the Welsh Borderland, and the rocks in which they occur, are described.

I. Introduction and Previous Research

RECENT work on the stratigraphy of the Silurian of the Welsh Borderland, in particular the Woolhope inlier, Herefordshire, has revealed the presence of fish scales below, as well as within, the Ludlow Bone Bed. Numerous occurrences of fish scales have been described from the Ludlow Bone Bed over a wide area of the Welsh Borderland. Amongst the important references the earliest is in "The Silurian System" (Murchison, 1839), where Agassiz figures the commonly occurring fish fragments of the bone bed. Others are by Phillips (1848), Strickland (1853), Harley (1861), Stamp (1923), and Wickham King (1934). Stamp gives a synopsis of the widespread occurrences of fish scales in the Ludlow Bone Bed throughout the Welsh Borderland, and Wickham King lists the known fish remains in rocks up to and including the Ludlow Bone Bed. There are only a small number of records of fish remains found below the Ludlow Bone Bed. The earliest is by Phillips (1848, pp. 97–8 and 226–7) who found them in the highest Ludlovian beds of May Hill and Tortworth and traced them down to the Aymestry Limestone in the Malvern District. An important record is the occurrence of *Archegonaspis* [*Scaphaspis*] *ludensis* (Salter, 1859) in the Upper and Lower Ludlow of Shropshire (Lankester, 1868). Other records are by Symonds (1872) in the *Dayia* Shales; Straw (1927) from the Upper Whitcliffe Flags of the Ludlow District; Ball (1951) from an impersistent bone bed at the top of the Sedgley (Aymestry) Limestone on Turner's Hill, South Staffordshire; Rhodes (1953, p. 260) in the Aymestry Limestone of Shropshire during his work on the conodonts, and Lawson (1953, p. 87) in a phosphatized-fragment bed at the top of the Lower Longhope Beds (top of the *Dayia* Shales) of May Hill. Thelodont denticles are most commonly recorded, though *Onchus*, *Cyathaspis*, and "*Pteraspis*" fragments have also been found. Denison (1956) gives a list of most of the known records of Ludlovian fish remains.

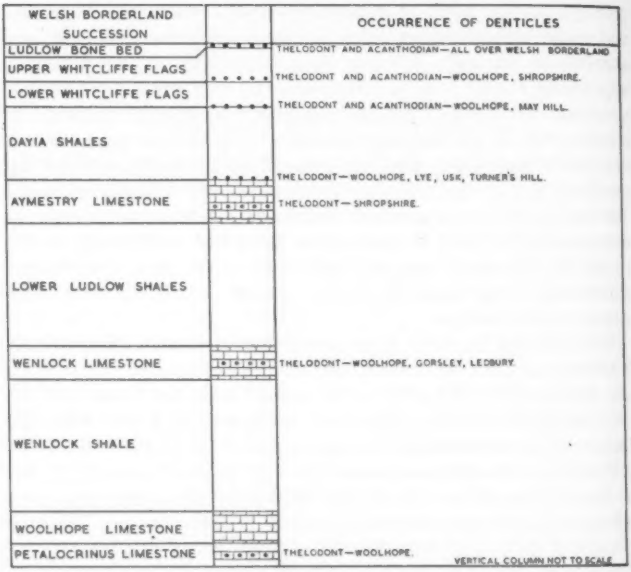
II. New Occurrences in the Ludlow Series

A detailed study of the Ludlovian succession in the southern part of the Woolhope inlier has revealed the presence of several condensed fragmentary beds occurring at various horizons between the Aymestry Limestone and the Ludlow Bone Bed. They vary in lithology from shell-fragment limestones to beds similar in lithology to the Ludlow Bone Bed. They were examined for their microscopic fauna and amongst several types of conodonts, horny brachiopod fragments, and other miscellaneous remains, there occurred thelodont and acanthodian remains. The two types of denticles are very similar in appearance, but they can be differentiated on their internal and external structure, one of their most obvious differences being the presence of a pulp cavity in the thelodont denticle. Acanthodian denticles have not been found lower than the base of the Lower Whitcliffe Flags (see Text-fig. 1 for the Ludlovian classification of the Welsh Borderland). The denticles are quite small and do not have the wide variety of form characteristic of those in the Ludlow Bone Bed itself, being square, round, or rectangular and not bigger than 1 mm. along their longest dimension. They generally become smaller in size the lower they occur in the succession.

Beds yielding denticles have been found over much of the South Woolhope area, i.e. south of a line joining Fownhope (SO/5778 3456) and Rushall (SO/6405 3497). The highest bone bed horizon within the Ludlovian succession occurs near the base of the Upper Whitcliffe Flags, and is well displayed in a quarry (SO/6440 3306) 500 yards W. of Bounds and in a stream exposure (SO/6573 2847) 350 yards N. 12° W. of Upton Court Farm. This bone bed is quite rich in thelodont denticles, and acanthodian denticles also occur in small numbers. Towards the top of the Lower Whitcliffe Flags occur several thin beds (up to 1 inch in thickness) consisting mainly of broken shell fragments, and containing both types of denticles. These beds can be examined in a quarry (SO/6524 3200) 50 yards N.E. of Bodenham Farm and in the stream exposure mentioned above near Upton Court Farm. At the top of the *Dayia* Shales a good bone bed is developed. It is a persistent condensed horizon over most of South Woolhope and can be seen in an exposure (SO/6517 3197) 10 yards W. of Bodenham Farm, in a quarry (SO/6426 3103) 230 yards N.E. of Welsh Court, and in the stream exposure near Upton Court Farm. It is characterized by the abundance of horny brachiopod fragments, but thelodont and acanthodian denticles have also been found, though the latter are rare. At the base of the *Dayia* Shales the succession is characterized by the occurrence of conglomeratic beds containing shell fragments and lenticular pebbles up to 2 inches in length. They are widespread over South Woolhope and contain thelodont denticles in small numbers.

A good exposure of these beds can be seen in a quarry (SO/6366 3150) 150 yards N. 35° W. of Dean's Place.

In the Ludlovian succession outside the Woolhope area, examination of shell fragment or conglomeratic beds has revealed the presence of small thelodont denticles at the base of the *Dayia* Shales in the Usk inlier (specimens collected from temporary excavations at SO/333 960



TEXT-FIG. 1.—The occurrence of thelodont and acanthodian denticles in the Welsh Borderland.

near Llandegveth) and in the Lye inlier, South Staffordshire (The Hayes, SO/929 845). Similar beds are found at this horizon throughout much of the Welsh Borderland, and it is likely that further work will reveal the presence of denticles at the base of the *Dayia* Shales over all the area.

III. Occurrences in Pre-Ludlovian Rocks

Further down the Silurian succession specimens of shelly Wenlock Limestone collected from Woolhope (near Canwood, SO/6130 3810), Gorsley (Linton Quarry, SO/677 257), and near Ledbury (Ledbury Council Quarry, SO/717 384) have yielded small thelodont denticles.

Some *Petalocrinus* Limestone from near the top of the Llandovery Series of the Woolhope inlier (from the type locality near Upper Littlehope, SO/5834 3658) has also yielded a few thelodont denticles. There are no previous records of thelodont denticles below the Aymestry Limestone in England and Wales, and as a result of this work their range is extended down to the top of the Llandovery Series. Specimens of thelodont denticles from the Wenlock and *Petalocrinus* Limestones are registered in the British Museum (Natural History).

The lowest occurrence of fish remains in Scotland is not known precisely, but according to Westoll (1951) the fish beds of Lesmahagow, Hagshaw Hills, and Pentland Hills are of late Wenlock or early to middle Ludlow in age. The lowest known occurrence of thelodont denticles is in central-western Colorado, where Stetson (1931) found them in the Harding Sandstone which is Middle Ordovician in age.

IV. Conclusions

The South Woolhope area is particularly favourable for the examination of those microscopic faunas which occur in bone bed accumulations. The Ludlovian sequence is condensed, halts in deposition being represented by deposits in which bony material is concentrated. Many of the Welsh Borderland Silurian areas have a fuller succession and thus condensed beds are absent or only poorly developed. This, however, does not preclude the presence of fish remains, but if they are present, which is likely, they will be very scattered. Similarly, as there are no bone beds in the Llandovery or Wenlock Series no concentrations of fish remains have been found, but thelodont denticles are present, though even more scattered than in the Ludlovian.

Acknowledgments

I wish to express my gratitude to Dr. J. D. Lawson, Mr. J. D. D. Smith, and Mr. H. A. Toombs for their generous advice during the preparation of this paper. I am indebted to Dr. I. Strachan for his instruction in the preparation of rock specimens for microscopic studies.

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A note on kyanite in the Moine Series of Southern Ross-shire, and a review of related rocks in the Northern Highlands of Scotland

By T. N. Clifford

Abstract

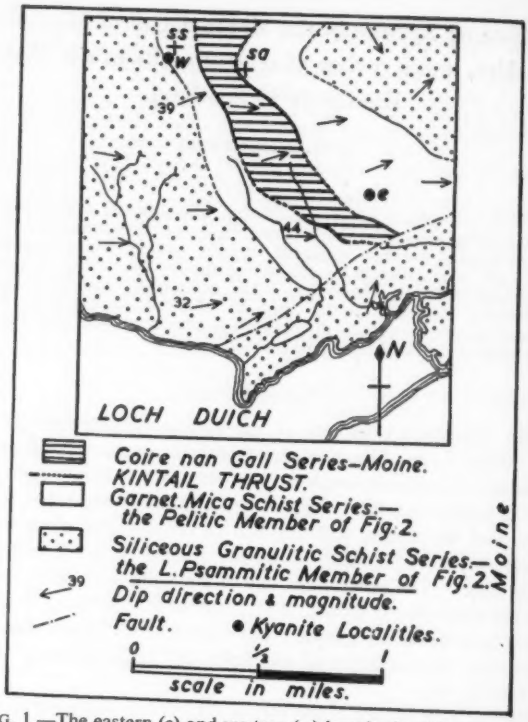
New occurrences of kyanite-bearing schists in the Moine Series in southern Ross-shire demonstrate the order of appearance of the typomorphic minerals staurolite, kyanite, garnet, and sillimanite, and are of significance in elucidating the relationship of regional metamorphism to orogenesis. The scarcity of *kyanite* in the Northern Highlands is the result of both isochemical and allochemical effects, and its distribution is compared with that of its polymorphs *andalusite* and *sillimanite*.

1. Introduction

THE comparative scarcity of the alumino-silicate *kyanite* in the Moine Series of the Northern Highlands warrants the description of two new localities in southern Ross-shire, which throw light on the order of appearance of the typomorphic minerals staurolite, kyanite, garnet, and sillimanite, and are also of considerable significance in elucidating the relationship of metamorphism to orogenesis in the Moine Series. The general geology of southern Ross-shire has been described elsewhere (Clifford, 1957); suffice it, therefore, to say that the two localities are in garnetiferous mica schists of the Moine on the *eastern* and *western* limbs of the Sgùrr an Airgid isoclinal syncline (see Text-fig. 1).

Although a large part of the Moine area of the Northern Highlands of Scotland undoubtedly lies within the Barrovian *kyanite-zone* of regional metamorphism (Barrow, 1893 and 1912), the index mineral has, to my knowledge, only been recorded in rocks of unquestionable Moine age from four other districts (see Text-fig. 2 [1]), which are as follows: (1) east of Cnoc an Eireannaich, central Sutherland (Read, 1931, p. 33); (2) around the Carn Chuinneag and Inchbae pre-foliation granitic intrusives, eastern Ross-shire (Peach and others, 1912); (3) east of Sgùrr a' Phollain, Erchless Forest, Inverness-shire (Horne and others, 1914, p. 26); and (4) Ross of Mull (Bosworth, 1910). The host rock of these kyanites is of pelitic or semi-pelitic composition and all of the localities lie within the " western limit of regional injection " of the Moine Series as defined by A. G. MacGregor (1952).

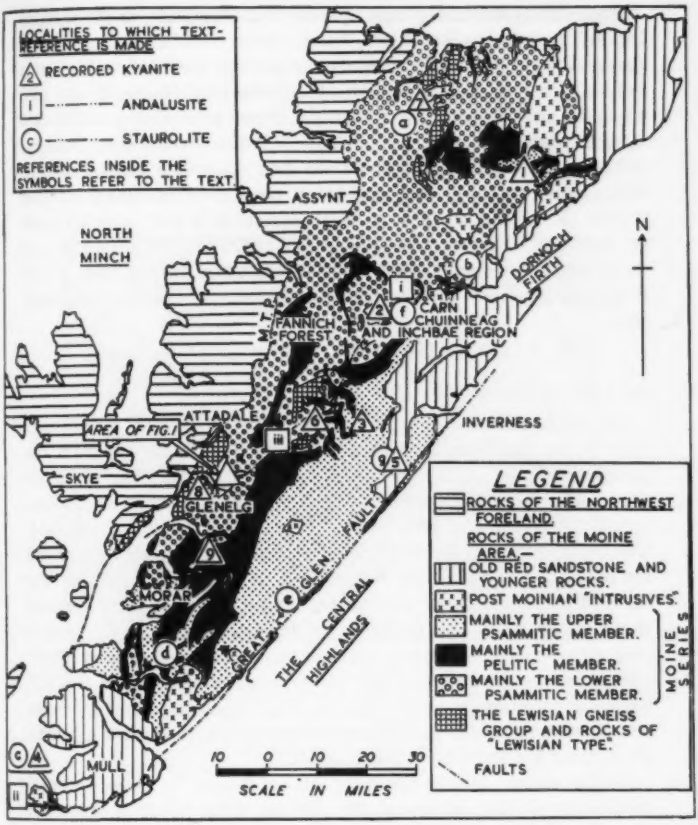
[1] The Moine stratigraphy in Text-fig. 2 is based on correlations given elsewhere (Clifford, 1954 and 1957), and represents an extension and amplification of the stratigraphic column established by Richey and Kennedy (1939) in the Morar district of Inverness-shire. The detailed basis for these correlations will be described in a future publication.



TEXT-FIG. 1.—The eastern (e) and western (w) kyanite localities on the limbs of the Sgùrr an Airgid isoclinal syncline, southern Ross-shire. Abbreviations: sa, Sgùrr an Airgid; ss, Sgùrr na Seamraig.

In addition, there are records of kyanite from five other districts within the Moine area, in rocks of Lewisian age or in rocks whose age is disputed or is unknown. These localities are as follows: (5) the "Lewisian inlier" of Glen Urquhart,[1] Inverness-shire (Horne and others, 1914, pp. 21–2); (6) the "Lewisian inlier" west of Sgùrr Fhuartuill, central Ross-shire (Peach and others, 1913, p. 51); (7) the undifferentiated Moine and Lewisian-type rocks south-east of Dherue, central Sutherland (Read, 1931, p. 40); (8) the *bonafide* Lewisian inlier of Glenelg (Clough *in* Peach and others, 1910) and its

[1] Specimens of the kyanite-mica schists of Glen Urquhart have been examined from the collections of the Department of Geology of the University of Leeds and, on the basis of experience with kyanite-bearing pelites of both Moine and Lewisian age in southern Ross-shire, they are considered to be of the Moine age.



TEXT-FIG. 2.—Generalized geological map of the Northern Highlands to show the distribution of recorded kyanite, andalusite, and staurolite within the Moine area. The bedrock geology is, in part, taken from the Geological Survey 1: 625,000 map (1948). The stratigraphic column is an amplification of that established in the Morar District by Richey and Kennedy (1939), extended northwards in the manner suggested elsewhere (Clifford, 1954 and 1957). The units of Moine stratigraphy are, of necessity, generalized and, in particular, the Pelitic Member outcrop contains significant infolds of the overlying and underlying members.

northward continuation at Inverinate (Clifford, 1957); and (9) on Sgùrr a' Choire bheithe, Knoydart, Inverness-shire (Heddle, 1924, p. 61), in rocks whose age is at present not known.

Staurolite is associated with kyanite, and sillimanite, at the western locality in southern Ross-shire, but is scarce elsewhere in the Moine Series of the Northern Highlands and is only recorded, as far as is known, from (*a*) near Loch Meadie, Sutherland (Read, 1931); (*b*) south of Loch Lànnsaidh, Sutherland (Read and others, 1925); (*c*) Ross of Mull (Bosworth, 1910); (*d*) Moidart, Inverness-shire (Richey, 1931, p. 64); (*e*) around the Glen Loy Complex, Inverness-shire (MacGregor, 1953, p. 45); and (*f*) in the Carn Chuinneag–Inchbae district (R. I. Harker, 1954, p. 449); Staurolite is also recorded from (*g*) the Glen Urquhart " Lewisian inlier " (Francis, 1956, p. 356) and its presence was *suspected* by Teall (*in* Peach and others, 1910, p. 19) in kyanite gneisses in the Lewisian Gneiss Group of Glenelg, Inverness-shire.

2. Kyanite Associations in Southern Ross-shire

(*a*) *Field Relations.*

The most extensive kyanite occurs at the locality on the western limb of the Sgùrr an Airgid syncline, 70 yards S. 20° W. from the summit of Sgùrr na Seamraig (see Text-fig. 1), where the rocks are predominantly kyanite-garnet-muscovite-tourmaline schists with microscopic sillimanite and staurolite. They are associated, in the field, with concordant and discordant tourmaline-bearing quartz veins which are generally not more than 3 in. to 6 in. in width. The veins are the focus of concentration of tourmaline, suggestive of a genetic relationship between quartz vein emplacement and tourmalinization. Associated with the kyanite-bearing rocks are garnet-biotite-muscovite schists and gneisses which advertise their presence within the zone of regional pegmatite injection by the occurrence of (*a*) oligoclase porphyroblasts and (*b*) augen and stringers of trondhjemite pegmatite; such injection phenomena are sporadic at this locality.

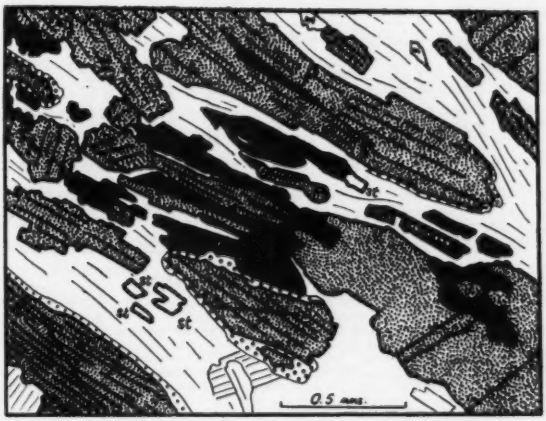
At the western locality described above, kyanite is visible in hand specimen. At the eastern locality, on the other hand, it occurs as microscopic inclusions in large porphyroblasts of almandine in a garnet-muscovite-biotite schist close by the deer fence 1,200 yards S.E. of the summit of Sgùrr an Airgid. The garnets are up to 3 cm. in diameter and, once again, occur in rocks with associated regional pegmatite injection but, in this case, with neither quartz-veining nor tourmalinization.

(*b*) *Petrography and Chemistry.*

Kyanite-sillimanite-staurolite-garnet Schists of the Western Locality (see Text-fig. 3).—The major constituents of this rock are muscovite, kyanite, garnet, columnar crystals of tourmaline, staurolite, and brushform sillimanite. Accessory minerals include oligoclase, magne-

tite, zircon, and apatite. Chlorite is present as an alteration product of garnet.

In Table 1 the bulk analysis of this rock (analysis A) is compared with published analyses of kyanite-bearing pelitic rocks from the Moine Series of the Northern Highlands (analyses B, C, D, and E), indicating that the southern Ross-shire kyanite-rock contains higher percentages of alumina, potash, and combined water, and less silica than analysed kyanite-bearing rocks from elsewhere.



TEXT-FIG. 3.—Kyanite (heavily stippled), garnet (black), and staurolite (st), with muscovite (little ornamented) in the schist from the western locality. Heavy dots around certain of the kyanite crystals represent " aureoles " of fine-grained muscovite and sillimanite. Accessory minerals include magnetite (m). This text-figure is drawn from a photomicrograph.

Muscovite ($n_\beta - 1{\cdot}599 \pm 0{\cdot}003$ [1]) makes up the bulk of the rock. It occurs mainly as large flakes up to 3 mm. in diameter, but is also seen as inclusions of varying size in all other major constituents. It represents, therefore, in large part, the earliest primary mineral phase of the present mineral assemblage. In association with fibrolite-sillimanite, a fine-grained variety of muscovite forms " rims " of up to 0·1 mm. in width around some of the blades of kyanite.

Kyanite is the second most abundant mineral and is disposed both as discrete blades up to 1·5 mm. in length, and as fine-grained granular aggregates. The larger crystals show the effects of concertina-crumpling and simple folding which, in extreme cases, have resulted in rotation of

[1] All refractive index measurements presented in this paper have been determined under sodium light at 22° C., and are correct to $\pm$ 0·003.

kyanite blades through angles of 70° and more. From the abundant fracturing which invariably accompanies such crystal folding it is concluded that deformation postdated kyanite crystallization. Folding is also seen in the muscovite at this locality and elsewhere in southern Ross-shire (Clifford, 1954, Plate xviii (*d*)). Bosworth (loc. cit.) noted

TABLE 1

	(A)	(B)	(C)	(D)	(E)	(F)	(G)	(H)	(I)
SiO_2	42·70	62·85	61·87	60·91	65·98	58·77	63·98	59·54	58·29
TiO_2	0·60	0·88	0·86	1·20	1·69	1·17	0·85	1·01	1·13
Al_2O_3	37·71	20·58	20·94	20·45	14·59	19·69	17·68	19·55	19·53
Fe_2O_3	1·09	1·10	1·06	1·40	0·31	0·88	2·23	0·81	1·02
FeO	5·23	5·10	4·76	5·29	5·19	6·88	4·76	6·03	6·85
MnO	0·17	0·04	0·05	0·03	0·09	0·07	0·05	0·08	0·13
MgO	1·01	1·45	1·50	1·35	3·38	2·43	3·18	2·73	2·24
CaO	0·58	0·72	0·77	0·91	0·58	1·61	1·05	1·85	2·30
Na_2O	1·25	1·67	1·44	1·26	3·87	1·95	1·10	1·88	2·25
K_2O	5·89	4·06	4·32	4·06	2·88	3·68	4·16	3·68	3·59
H_2O+	3·51	0·97	2·24	2·21	0·90	2·20	1·18	1·80	2·00
H_2O-	0·17	0·17	0·04	0·20	0·18	0·12	0·10	0·10	0·08
P_2O_5	0·04	0·16	0·18	0·55	0·18	0·31	0·08	0·30	0·31
CO_2	—	—	—	—	—	—	—	0·01	—
FeS_2	—	—	—	—	—	0·00?	0·00?	0·13	0·00?
Cr_2O_3	—	—	—	—	—	0·01	0·01	—	0·01
C	—	—	—	—	—	—	—	0·29	—
BaO	—	—	—	—	—	0·08	0·00?	0·09	0·09
	99·95	99·75	100·03	99·82	99·82	99·85	100·41	99·88	99·82

EXPLANATION OF ANALYSES IN TABLE 1

(A) Bulk analysis of kyanite-sillimanite-staurolite-garnet-muscovite schist, 70 yards S. 20° W. of Sgurr na Seamraig, southern Ross-shire. Analyst, M. H. Kerr (new analysis).

(B) " Chiastolite " hornfels taken from 50 yards S. of the summit of Sgor a' Chaoruinn, Ross-shire. Analyst, R. I. Harker.

(C) Muscovite-rich garnetiferous hornfels with biotite and some recrystallized kyanite. Half mile E. of Carn Sonraichte and in Allt Sron Fhearchair. Analyst, R. I. Harker.

(D) Deformed " chiastolite " hornfels with muscovite, biotite, and garnet. Staurolite occurs in association with kyanite of the pseudomorphs after andalusite. Half mile N.N.W. of the summit of Sgor a' Chaoruinn, i.e. at the W. end of Loch a' Chaoruinn. Analyst, R. I. Harker.

(E) " Cordierite " (now kyanite, biotite, and shimmer aggregate) hornfels. Half mile S. of Mullach Creag Riaraidh and in Diebidale River. Analyst, R. I. Harker.

(F) Garnet-sillimanite-staurolite-mica schist (pelitic schist). Band in the Moine Schists, 1,700 yards N. 15° W. of Dalelia, Loch Shiel, Moidart, Inverness-shire. (Quoted from Summary of Progress of the Geological Survey of Great Britain for year 1934, p. 83.) Analyst, C. O. Harvey.

(G) Staurolite garnet schist in Moine Series, one-third mile S.E. of Cairn on Cnoc an Daimh Beag, 1¼ miles E. of Loch Meadie, Altnaharra, Sutherland. (Quoted from Read, 1931, p. 40.) Analyst, B. E. Dixon.

(H) Pelitic Schist, 500 yards W. 29° N. of Upper Letters Cottage, Corriemulzie, Ross-shire. (Quoted from Read, 1926, p. 136.) Analyst, F. R. Ennos.

(I) Garnetiferous mica schist (pelitic schist). Band in the Moine Schists, 170 yards W. 10° S. of the S. end of Loch Blain, near Acharacle, Moidart. (Quoted from the Summary of Progress of the Geological Survey of Great Britain for year 1934, p. 83.) Analyst, C. O. Harvey.

Analyses (B) to (E) inclusive are quoted from R. I. Harker (1954).

the occurrence of folded kyanite crystals in Ross of Mull, and examples of this type testify to the overlap between regional metamorphism and folding and serve to support the multiphase nature of Moine metamorphism suggested by J. G. C. Anderson (1956, p. 30).

The rock is peppered with the cyclamen-pink coloured garnets so typical of metamorphosed pelitic rocks of the Moine Series. Inclusions of kyanite and muscovite are common in the garnet which is frequently seen developing directly from kyanite. The absence of biotite and

quartz from the rock supports the following reaction for garnet formation:—

$$\underset{\text{iron-rich biotite}}{2K\,(Fe,\,Mg)_3\,AlSi_3O_{10}(OH)_2} + \underset{\text{kyanite}}{4Al_2SiO_5} + \underset{\text{quartz}}{2SiO_2} \rightleftharpoons \underset{\text{iron-rich garnet}}{2(Fe,\,Mg)_3\,Al_2(SiO_4)_3} + \underset{\text{muscovite}}{2K\,Al_2AlSi_3O_{10}(OH)_2}$$

That garnet freely replaces folded and fractured kyanite but does not itself exhibit any signs of deformation, either as " crushing " or as " snowballing ", shows that its formation took place after the close of the phase of deformation of kyanite.

Staurolite is widely present in small idio- and xenoblastic crystals which are generally less than 0·15 mm. in size but which are, occasionally seen as porphyroblasts up to 1 mm. in length.

Small needles of sillimanite (usually less than 0·1 mm. in length) in brushlike aggregates are developed as a recrystallization of the marginal portions of some kyanite blades, and the undeformed nature of the delicate needles indicates that the mineral is a late crystallisate. On the other hand, however, inclusions in tourmaline of kyanites with sillimanite " rims " show that sillimanite crystallization antedated tourmalinization.

Tourmaline is widespread and forms columnar crystals up to 2 cm. in length. Its optical properties are as follows: $n_e = 1{\cdot}631$, $n_o = 1{\cdot}657$; E = pale straw-yellow, O = dark greenish-brown. Sp. gr. = 3·14.

Semiquantitative spectrographic analysis of the tourmaline shows the important oxide percentages to be of the following order (the range of accuracy is given in brackets): CaO, 0·5 (0·41–0·53); MgO, 8·3 (7·8–8·7); FeO (determined as Fe_2O_3), 4·7 (3·4–5·9); Na_2O, 1·3 (0·8–1·8); MnO, tr; Li_2O, tr.

In terms of the tourmaline end-members, these results indicate a general tourmaline composition as follows:—

$$(\text{Dravite})_{62-67}\,(\text{Schorlite})_{20-25}\,(\text{Uvite})_{10-14}$$

These figures are consistent with the optical data in the light of determinative tables given by Winchell (1951).

The tourmaline " includes " fragments of coarse muscovite, kyanite, euhedral garnet, staurolite, and sillimanite which, in view of the mineral relations described above, indicates that the order of formation of the major constituents of this rock from the *western* locality has been as follows:—

(i) Coarse muscovite; (ii) kyanite-staurolite—phase of deformation—(iii) garnet-sillimanite; (iv) tourmaline.

Kyanite-garnet Schist of the Eastern Locality.—The kyanite occurs

here as irregularly shaped inclusions up to 0·5 mm. in size in large poeciloblastic cyclamen-pink garnets in a garnetiferous muscovite-biotite-quartz-oligoclase schist of the Moine Series. The inclusions are small and do not show any particularly intense deformation and indicate, once again, that kyanite is a demonstrably earlier crystallisate than garnet. Other " included " minerals are quartz, biotite, muscovite, oligoclase, magnetite, apatite, rutile, and sphene.

Red-brown biotite flakes of the country rocks are seen under the microscope to terminate abruptly at the margins of the garnets. Biotite

TABLE 2.—REGIONAL METAMORPHIC GARNETS FROM THE PELITIC ROCKS OF THE MOINE SERIES

SiO_2	36·93	36·90
TiO_2	—	0·05
Al_2O_3	21·50	21·93
Fe_2O_3	1·12	0·40
FeO	32·33	34·85
MgO	3·37	2·99
MnO	2·66	0·67
CaO	2·05	2·58
H_2O+	0·20	—
	100·16	100·37
Percentages of garnet molecules—		
Almandine	76·2	80·87
Pyrope	11·4	10·13
Spessartine	6·0	1·50
Andradite	3·6	2·05
Grossularite	2·8	5·45

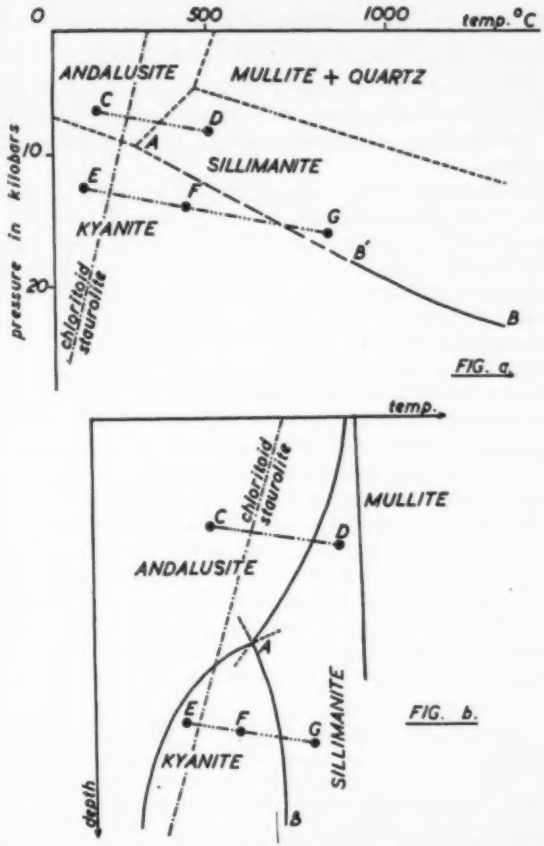
Localities—

(*a*) Almandine from the Garnetiferous Mica-Schists Series of the Moine Series. 1,200 yards south-east of summit of Sgùrr an Airgid, southern Ross-shire. (Quoted from Clifford, 1957.) Analyst, M. H. Kerr.

(*b*) Almandine from muscovite-rich garnetiferous hornfels. Half mile east of Carn Sonraichte and in Allt Sron Fhearchair, Carn Chuinneag–Inchbae aureole. (Quoted from Harker, 1954.) Analyst, R. I. Harker.

also occurs, however, in large quartz-rich inclusions within the outer margins of garnet, in contrast to the more compact interiors where biotite has been totally digested and inclusions are confined to muscovite, kyanite, and quartz in very much smaller grains than in the marginal portions of the garnet porphyroblasts.

In appearance the garnet is the typical variety found in the regionally metamorphosed pelites of the Moine Series, and, in its chemical composition (see Table 2), simulates the garnet from Carn Chuinneag which R. I. Harker (1954) regards as of regional metamorphic origin. At Carn Chuinneag regional metamorphic kyanite developed at the



TEXT-FIG. 4.—A generalized curve of inversion of chloritoid to staurolite, superimposed on the phase relations of alumino-silicates suggested by:—

(*a*) Clark (and others, 1957), and
(*b*) Korjinsky (1937).

The scale of the two diagrams is *not* the same. Curve B–B′ of Text-fig. 4 (*a*) has been experimentally determined by Clark.

expense of andalusite which formed as a contact metamorphic product around the prefoliation Carn Chuinneag and Inchbae granites. There, as in southern Ross-shire, R. I. Harker has demonstrated the appearance of garnet at a stage later than the crystallization of kyanite.

3. General Discussion

(*a*) *Kyanite and its Related Alumino-silicate Polymorphs.*

In view of the work of Korjinsky (1937), Miyashiro (1949), Thompson (1955), and Clark (and others, 1957), the suggestion by Harker (1939) that " shearing stress " is a pre-requisite for kyanite formation cannot be sustained.

The most recent views, of Clark (loc. cit.) on the pressure-temperature relations of the alumino-silicates, andalusite, kyanite, sillimanite, and mullite are given in Text-fig. 4 (*a*). Clark follows Miyashiro (loc. cit.) and Thompson (loc. cit.) in suggesting that in the lower pressure field, kyanite may be the stable form inverting, with rise in temperature, to andalusite. In contrast, Korjinsky (loc. cit.) visualizes a very different relationship (Text-fig. 4 (*b*)) based on observed field relations. He recognizes that at the high pressures generated at depth, andalusite, kyanite, and sillimanite are the stable forms at low, medium, and high temperatures respectively. It is not the purpose of this paper to debate the two opposing views given in Text-figs. 4 (*a*) and (*b*), which differ *basically* in their interpretations of kyanite-andalusite relations, and show good *general* agreement for andalusite-sillimanite and kyanite-sillimanite relations; the latter, experimentally determined by Clark (loc. cit.), is of greatest interest to this paper. When the generalized curve of chloritoid inversion to staurolite, given by Francis (1956),[1] is related to the field of stability of alumino-silicates in Text-figs. 4 (*a*) and (*b*), the kyanite-sillimanite-staurolite assemblage from southern Ross-shire represents the product of a right-ward transition *of the type* of curve F–G. Text-fig. 4 also relates, in a general way, the

[1] The chloritoid-staurolite curve given in Text-fig. 4 is positioned to accommodate the appearance of staurolite in association with the triple-point assemblage of kyanite, andalusite, and sillimanite, described by Heitanen (1956). The negative slope is based on the reactions:—

5 kyanite + 4 chloritoid $\rightleftharpoons$ 2 staurolite + silica + water.
9 chloritoid $\rightleftharpoons$ 2 staurolite + silica + 5 ferrous oxide + 8 water.
In contrast, the curve of reaction:—

chloritoid + quartz $\rightleftharpoons$ staurolite + garnet

should have a positive slope and preliminary experimental work by Halferdahl (1957, p. 227) shows this to be the case. Halferdahl's results further show this to be a relatively high temperature reaction which would lie on the high temperature side of the kyanite-andalusite-sillimanite triple-point predicted by Clark (see Text-fig. 4), and would lead one to expect chloritoid-kyanite-sillimanite-andalusite as a possible stable assemblage somewhere in the world.

From the above evidence it is abundantly clear that, if the position of this kyanite-andalusite-sillimanite triple-point is approximately correct, there are at least two very different and well-defined sets of physical conditions under which staurolite is generated from chloritoid, a fact which will render any " staurolite isograd " to be ambiguous unless the reaction of formation of the staurolite can be demonstrated.

"normal" (assemblages 6 to 10) and "abnormal" (assemblages 1 to 4) regional metamorphic assemblages as follows:—

Low Pressure (increasing temperature from 1 to 5; exemplified by C–D of Text-figs. 4 (*a*) and (*b*)):

(1) andalusite-chloritoid
(2) andalusite-chloritoid-staurolite
(3) andalusite-staurolite
(4) andalusite-sillimanite-staurolite
(5) sillimanite-staurolite

High Pressure (increasing temperature from 6 to 10; exemplified by E–G of Text-figs. 4 (*a*) and (*b*)):

(6) kyanite-chloritoid
(7) kyanite-chloritoid-staurolite
(8) kyanite-staurolite
(9) kyanite-sillimanite-staurolite
(10) sillimanite-staurolite

(*b*) *Alumino-silicates in the Moine Series of the Northern Highlands.*

The regional but sporadic distribution of kyanite localities in the Moine Series in the Northern Highlands indicates that physical conditions were not primarily responsible for the absence of the kyanite-zone; *chemical features of the rock have exercised the principal control* as might be suspected.

Comparison of analyses of kyanite-free rocks unaffected by significant regional pegmatite permeation (Table 1, analyses F, G, H, and I) with kyanite-bearing rocks from southern Ross-shire and Carn Chuinneag (Table 1, analyses A, B, C, and D) show marked differences in the two groups. Most notably, in the kyanite-free types the ratios of ($FeO + Fe_2O_3$), MgO, CaO, and Na_2O to Al_2O_3 are generally greater than in kyanite-bearing types thereby encouraging the generation of such minerals as plagioclase and garnet in the former, in preference to kyanite. Read (1931) has shown the addition of soda to be characteristic of rocks within the zone of regional injection and permeation. The introduction of this oxide and its fixation by alumina and silica has probably been another important factor in the inhibition of kyanite formation.

In contrast, the development of *sillimanite* is normally not dependent on the presence of excess alumina at lower temperatures for it often develops as a breakdown product at the upper temperature of stability of biotite (Tozer, 1955), or of staurolite-quartz, and muscovite-quartz (Turner and Verhoogen, 1951) assemblages. For this reason sillimanite has attained unrestricted development in the Northern Highlands from Mull northwards to the coast of Sutherland (see Phemister, 1948). It occurs in two important generations as follows: (*a*) as a widespread

product of high-grade regional metamorphism in association with the regional pegmatite injection in the Moine Series and, (*b*) as a later contact-metamorphic mineral in local aureoles around the " Newer " intrusives of Ross of Mull (Bosworth, 1910) and Glen Loy (MacGregor, 1953, p. 45).

Andalusite, on the other hand, has been recorded in only two districts in Moine rocks, namely: (i) in the pre-regional metamorphic contact aureole of the pre-foliation Carn Chuinneag and Inchbae granitic intrusives (Peach, and others, 1912), and (ii) in association with sillimanite in the post-regional metamorphic aureole of the Ross of Mull granite (Bosworth, 1910). Andalusite has also been described from (iii) pelitic rocks of the " Lewisian inlier " of An Cruachan, central Ross-shire (Peach, and others, 1913, p. 51).

From the accumulated evidence it is clear that alumino-silicates developed at three important phases in the metamorphism of the Moine Series of the Northern Highlands. Firstly, chiastolite developed locally around the Carn Chuinneag–Inchbae granites. Secondly, kyanite and sillimanite were generated during regional metamorphism in part during orogenesis and accompanied by intense injection and permeation; all of the known occurrences of kyanite in the Moine Series belong to this phase. Thirdly and finally, sillimanite and andalusite developed in the post-orogenic period as local contact metamorphic products in the aureoles around certain of the " Newer " (Caledonian) intrusives in the Northern Highlands.

It is significant that in southern Ross-shire, the regional metamorphism is polyphase and can be subdivided on the basis of the aluminosilicates kyanite and sillimanite into para- and post-deformational assemblages. In the light of this recognition and in view of the late appearance of garnet any simple zonal scheme of regional metamorphism in the Scottish Highlands is suspect if it omits consideration of the order of generation of the typomorphic minerals.

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Post-Tectonic Granite-Gabbro Complexes in South-eastern Queensland

By R. Gradwell

Abstract

Work on post-tectonic complexes in South-eastern Queensland has led to a general hypothesis concerning their formation. The earliest rocks, the gabbros, are intrusive, and these are followed by metamorphic trondhjemitic types which become progressively more granodioritic and finally granitic. The true granites act intrusively towards the earlier rocks of the complex.

In a recent investigation the author (Gradwell, 1958) described an occurrence where diorite had been intruded into siliceous mudstones causing a thermal metamorphism of a common type around much of the margin. However, in one part of the area, it was found that the metamorphism had proceeded further to give rise to a rock showing all stages of metamorphism, set in a more recrystallized base. In part, this base is similar to the hornfels common elsewhere, and it grades from this into a rock of a texture similar to a granodiorite.

The dioritic rock described, the Kholo Creek quartz-diorite, is a post-tectonic mass considered to belong to a group of granito-dioritic masses emplaced in the Brisbane Metamorphics in the structural unit known as the D'Aguilar Block. The rocks in these masses range from granite to gabbro, being predominantly granodioritic. The Kholo Creek quartz-diorite is considered to have been emplaced by intrusion to a relatively shallow depth, and the agmatitic rock is considered to have formed by recrystallization and replacement of the country rocks, due to heat and addition of material from an unknown source at depth. This change may have been assisted by the intrusion of the quartz-diorite but it is not thought that the intrusion of the quartz-diorite was directly responsible for the agmatite. It is stressed that the localization of the recrystallization has been the cause of formation of the xenoliths and it is suggested that with a more complete change and with subsequent addition of potash feldspar, a xenolith-bearing granodiorite would form.

It was earlier suggested (Gradwell, 1955) that the bulk of the Samford granodiorite to the north of Kholo Creek, formed in this way at depth and this granodiorite was later intrusively emplaced. Some of its margins show a more advanced stage of this agmatite formation.

The Kholo Creek exposure is convincing, but small, and demonstrates only a possible line of development which might be followed to give granodiorite in mass. The Samford area does not demonstrate so well the early stages of formation of the agmatitic trondhjemite.

The author thought it might be possible to test the hypothesis on a large scale by investigating the area coloured red and noted as " Granite, Granodiorite, and other acid plutonic rocks " in the north-west part of the Geological Map of the Moreton District, Queensland. After a short reconnaissance it was soon clear that within this area was a diversity of rocks of a post-tectonic relationship to Lower Palaeozoic (? ≡ Brisbane Metamorphic country rocks) ranging from granite to gabbro and having, as far as ascertained, similar age relationships to one another as do those of similar type in the D'Aguilar Block. That is, there are early gabbros followed by diorites, granodiorites, granites, in fact, the well-known basic to acid trend. The country rocks in the large area are similar, mostly low-grade (not above biotite grade) metasediments and volcanics.

Since the results of the reconnaissance work have led to more detailed investigations, largely concerning textures, it may be of interest to indicate the lines of development of these rocks which this work suggests. These ideas are presented in the hope that workers in better-exposed areas may test them, for in large parts of the north-west of the Moreton District there is a cover of laterite.

It has been found that the gabbros, and to a lesser extent the diorites, are typically magmatic in texture, with mostly well-defined crystals, commonly ophitically intergrown. They do not show much replacement of one mineral by another (except for low-temperature, hydrothermal alteration). They may show orientation of minerals due to movement and they rarely contain xenoliths, except perhaps locally at contacts. In many places in the field these rocks are seen to be cut by more acid types.

The sequence which follows is now proposed without putting forward any evidence, which will be set forth elsewhere. The sequence is, of course, a generalization and is not found necessarily in any one large area.

The first rock of this series is a trondhjemitic rock with andesine, quartz, and biotite, occasionally with other ferromagnesian minerals. The quartz and biotite form a groundmass which is in the early stages typically hornfelsic, while the plagioclase is porphyroblastic. This rock is usually characterized by an inhomogeneity of overall texture and varies in composition with the amount of inclusions.

Next there is a common type of granodiorite with less abundant, more definite inclusions; and with the minerals more even-grained and with potash feldspar appearing. With increase in this constituent we get the granodiorite which is the typical granitoid rock here.

With further increase in recrystallization and replacement of plagioclase by potash feldspar, there is developed a granite in which inclusions become rarer with progress of this change. In the true potash granites

which show intrusive characters with regard to their country rocks, the inclusions are local and not much altered. These potash granites in their textures are quite different from the rocks of the trondhjemite-granodiorite series, and they, like the gabbros, are regarded as intrusive rocks.

The generalized sequence of events then is:—

Intrusion of gabbroic rocks.

Formation of trondhjemitic rocks by recrystallization and replacement. In this the replacement is mainly by materials needed to form plagioclase. The amount of xenolithic material will depend on the composition of the country rock and the extent of the replacement.

The foregoing rocks grade into granodioritic rocks by further recrystallization and introduction of potash feldspar which replaces plagioclase (mainly). The material may be locally intrusive.

Further potash feldspar replacement is accompanied by greater mobilization of the mass so that granite which may be formed shows intrusive characters. The granites seen at present levels of exposure near granodiorites and trondhjemites are therefore thought to have formed, not in place, but from earlier rocks of the trondhjemite-granodiorite series, at deeper levels.

The part played by the early basic rocks is not clear at present. It is thought that their injection may be the means of bringing in some heat to the region, but nowhere do they appear to be responsible for anything but local metamorphism. Many of the diorites may be altered gabbros or perhaps gabbros which assimilated country rock at depth.

It is thought that this kind of plutonic activity does not involve high-grade regional metamorphism. Rather, the action seems to have taken place at all times on a restricted scale, with small masses of the altered country rocks gradually coalescing to form larger and larger masses which become more homogeneous. Certain rocks in the area, notably the quartzites, have acted as resister rocks.

The replacement processes will, of course, give rise to expulsion of certain constituents concomitant with introduction of others. In the formation of potash feldspar from plagioclase, for example, Ca and Na must be replaced by K, although it is noticeable that with progress towards the potash feldspar granite, the potash feldspar becomes more and more perthitic. The formation of the granite by replacement will mean, in general, the expulsion upwards of cafemic constituents. Further, with the intrusion of the granite without noticeable inclusion of earlier rock, there is the second problem, the room problem, of magmatic injection.

If the granite stage is to be regarded as a magmatic one, then we can expect that normal processes of concentration of rare constituents

may proceed here and so there may be a concentration of any material of the ore-mineral class. These may thus have come from the country rocks themselves through recrystallization changes or have been added from below. In regions containing various types of granito-dioritic rocks, therefore, one would expect to find concentration of sulphide and " pneumatolytic " minerals associated with the latest, most potash-rich, varieties.

In the area of the north-west of the Moreton District the author has not so far found any one small compact area where all these sequences are represented together. The D'Aguilar Block region has a more complete picture. One area which the author thinks is most suitable for investigating the hypothesis is in the south-west of Scotland, especially in the Loch Doon and the Cairnsmore of Carsphairn Complexes.

It must be understood that these granitic masses are all post-tectonic, and represent relatively high-level masses. The relationship of these changes to the upper parts of Read's Granite Series seems acceptable to the author, but he thinks that Read would not consider that they were placed in a level of sufficient energy for the proposed changes to go on.

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THE EVOLUTIONARY PLEXUS

SIR,—The concept that morphological species must be interpreted in terms of a " plexus of descent " is essential to the understanding of those who would use palaeontological data to further evolutionary theory. Recently I mistakenly credited Trueman with the introduction of this idea (*Syst. Assoc. Publ.*, 2, p. 2). It has been pointed out to me that the concept was first discussed by Swinnerton (*Outlines of Palaeontology*, 1923). I am sorry I made this mistake, for Swinnerton's textbook has contributed so much to the background thinking of the palaeontologists of to-day that we are apt to forget how many of his ideas were novel when the first edition of the work was published.

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DEVELOPMENT OF LINEATION IN COMPLEX FOLD SYSTEMS

SIR,—I have delayed commenting on the paper by Clifford, Fleuty, Ramsey, Sutton, and Watson, (Jan–Feb, 1957) in the hope that someone more familiar with the ground might do so before me. The attempted division of lineation into simple, multiple, and anomalous is admirable but I feel it has (1) led the authors into a compartmentalization which, in many cases, precludes the simple explanation in favour of the complicated. I also think that the paper is in places (2) overwritten, (3) jargon, (4) statistically invalid and (5) of spurious accuracy To deal with these points in order . . .

(1) The possibility of rotation simultaneously with, or during the closing stages of folding, does not seem to have been seriously considered. Yet, bent axial traces are shown in figs. 5, 10 and 7. In fig. 5 the clockwise drag of the wrinkles suggests that the wrinkles are related not to the minor fold depicted but to a major one on the " left ". In fig. 10 an axial trace concave side south, is crossed by " later " minor folds (whose axial traces are also bent). These features could be explained by clockwise torque (Mead 1920, or Billings 1954). For fig. 7 a similar explanation might also be applicable. Thus Clifford's lineations might be not two separate generations, but merely early and late lineations of the same generation. Rotation and direction of rotation might be established by the minor folding. (Incidentally if the Tarvie fold trace of fig. 7 were folded by the late antiform, surely the early lineation would plunge away from the antiform trace and not toward it ?)

(2) Many expressions hang. In what sense (vertical, lateral, philosophic) is a hinge, hinge line, turn over, used ? Why not also whip-around, turn-around, flop-over, stretch-out ? Why 26 words (top p. 16) to tell us that a fold plunges steeply ? What is the purpose of fig. 9 ?

(3) Antiform and synform, uncommon terms to geologists outside Scotland and Scandinavia, are not defined. The references do not help either. An antiform, presumably *resembles* an anticline. On page 7, Sutton and Watson mention the arching of an axial plane to produce an antiform. But Ramsay (fig. 6) shows axial traces of antiform and synform without showing the structures which have been arched to produce them. He goes on to speak of minor folds—but what is the relationship of these minor folds and the (presumably earlier) anticlines and synclines ? In fig. 8, Ramsay shows superimposed antiforms and synforms but shows no lithologic horizons nor anything so elementary as an anticline or syncline.

(4) Fig. 10 seems statistically invalid. A fold may have any number of axes. And presumably because the axial trace is bent, each axis would be bent. However Fleuty speaks of *the* fold axis ; does not show the distribution of the 250 foliation readings ; gives no indication of the scatter, and does

not show the " centroid " (point of emergence of his theoretical fold axis) on the map. The bent axial trace is blithely represented as an undistorted plane (fig. 10c), and, to make matters more interesting, the centres of all stereo-nets are omitted.

(5) Fig. 8, a map of country where variation in dip is extreme, shows dip symbols of 31°, 59°, 71°, etc. If these figures represented the average of several readings, they might be valid. Otherwise, only a combination of portable diamond saw, bubble-type clinometer, and several man-months of labour could yield results of such accuracy.

I realize that these remarks are in some ways unfair, as they apply to many other workers. However a serious attempt should be made *to fit together* field data *before* separating them by time barriers. Finally the stereographic projection is essentially a mode of presentation. Sometimes it can solve geological problems. It can also be used as window-dressing.

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